Design, Development, and Usability Evaluation of a Mobile Application for Monitoring Voice and Upper Airway Health

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Abstract

Introduction

Asthma and chronic obstructive pulmonary disease (COPD) are highly prevalent chronic respiratory diseases worldwide and in Canada. Despite the availability of telemonitoring methods, adequate symptom control in asthma and COPD remains a challenge due to the unpredictable nature of exacerbations and nighttime awakenings, which can lead to increased hospitalizations, healthcare costs and mortality. Mobile health (mHealth) applications (apps) provide a viable option to remotely monitor patients' health conditions and control symptom progression. The objectives of this thesis are to design, develop, and evaluate a mHealth app, namely AIrway, to support patients with asthma and COPD in symptom monitoring and self-management.

Methods

The AIrway app was designed and developed for Android smartphone devices in accordance with Morville's mobile app design principles and clinical guidelines, such as the Global Initiative for Asthma (GINA) and the Global Initiative for Chronic Obstructive Lung Disease (GOLD), to meet the needs of symptom monitoring. The app also complies with the Personal Information Protection and Electronic Documents Act (PIPEDA) and Quebec privacy law to ensure the protection of user information. Essential features include journaling asthma/COPD diaries, utilizing the Google Firestore cloud service for data storage, parsing local weather information, as well as sending medication reminders and action plans.

We recruited 5 app developers (i.e., technical raters) who were Computer Science Ph.D. students or post-doctoral fellows who took at least one mobile app development course or had at least one year of mobile app programming experience to evaluate the AIrway app. These technical raters completed the User Version of the Mobile Application Rating Scale (uMARS) survey, provided open-ended feedback, and responded to the IQVIA items after testing the app. The uMARS survey was designed to assess the app's engagement, functionality, aesthetics, and information quality while the IQVIA items were intended to assess the app's self-management functionality.

We collected, processed, and reported the uMARS and IQVIA data in accordance with the Checklist for Reporting Results of Internet E-Surveys (CHERRIES) guidelines to enhance the reliability of the findings. We also performed a literacy analysis using an open-source readability calculator to evaluate the app's contents.

Descriptive statistics of uMARS and IQVIA were computed and compared to the scores of similar self-management apps in the literature. A qualitative analysis of the open-ended feedback provided by the technical raters was also conducted to identify areas for product improvement.

Results and Discussion

The results indicate that the AIrway app was easily understandable to individuals with nine years of formal education. The app received a high uMARS overall mean score (3.6 out of 5.0) and an IQVIA overall median score (8 out of 11). These scores align with similar mHealth apps in the

literature (MARS: 3.0-4.2 and IQVIA: 6-10). The open-ended feedback suggested incorporating more graphical icons for better user interface display and improving the input field for the password reset function.

Overall, the app met the mobile app design principles and development guidelines, achieving appropriate colour contrast, readability, and layout presentations. Furthermore, asthma and COPD diaries, medication profiles, and action plans were developed based on clinically validated guidelines. These steps are essential to meet industrial standards and safeguard the app's credibility, accessibility, and usability. Future steps include expanding the app's compatibility to cross-platform frameworks to enhance the app's accessibility and equity.

Résumé

Introduction

L'asthme et la bronchopneumopathie chronique obstructive (BPCO) sont des maladies respiratoires répandues mondialement. Le contrôle des symptômes reste un défi malgré les méthodes de télésurveillance. Les applications de santé mobile (mHealth) permettent de surveiller à distance l'état de santé des patients. Cette thèse vise à concevoir, développer et évaluer l'application AIrway pour aider les patients asthmatiques et atteints de BPCO à surveiller et gérer leurs symptômes.

Méthodes

L'application AIrway a été conçue et développée pour les téléphones Android, en respectant les principes de conception d'applications mobiles de Morville et les directives cliniques telles que GINA et GOLD pour la surveillance des symptômes. Elle est également conforme à la LPRPDE et à la loi québécoise sur la protection de la vie privée pour assurer la protection des informations des utilisateurs. Les fonctions essentielles incluent un journal de l'asthme et de la MPOC, le stockage des données dans le service en nuage de Google Firestore, l'analyse des informations météorologiques locales et les rappels de médicaments et plans d'action.

Nous avons recruté 5 développeurs d'applications (évaluateurs techniques), étudiants en doctorat d'informatique ou post-doctorants ayant suivi au moins un cours de développement d'applications mobiles ou ayant au moins un an d'expérience dans la programmation d'applications mobiles, pour évaluer l'application AIrway. Ces évaluateurs techniques ont rempli la version utilisateur de l'échelle d'évaluation des applications mobiles (uMARS), ont fourni des commentaires libres et ont répondu aux questions d'IQVIA après avoir testé l'application. L'enquête uMARS a été conçue pour évaluer l'engagement, la fonctionnalité, l'esthétique et la qualité de l'information de l'application, tandis que les questions d'IQVIA ont été conçues pour évaluer la fonctionnalité d'autogestion de l'application.

Nous avons collecté, traité et présenté les données uMARS et IQVIA conformément aux directives CHERRIES (Checklist for Reporting Results of Internet E-Surveys) afin d'améliorer la fiabilité des résultats. Nous avons également effectué une analyse de la littératie à l'aide d'un calculateur de lisibilité en libre accès afin d'évaluer le contenu de l'application.

Les statistiques descriptives d'uMARS et d'IQVIA ont été calculées et comparées aux scores d'applications d'autogestion similaires dans la littérature. Une analyse qualitative des commentaires ouverts fournis par les évaluateurs techniques a également été réalisée afin d'identifier les domaines d'amélioration du produit.

Résultats et discussion

Les résultats indiquent que l'application AIrway a été facilement comprise par des personnes ayant neuf ans d'éducation formelle. L'application a obtenu une note moyenne globale élevée (3,6 sur 5,0) et une note médiane globale (8 sur 11) de la part d'IQVIA. Ces scores s'alignent sur ceux d'applications mHealth similaires dans la littérature (MARS : 3.0-4.2 et IQVIA : 6-10). Les

commentaires ouverts suggèrent d'incorporer plus d'icônes graphiques pour un meilleur affichage de l'interface utilisateur et d'améliorer le champ de saisie pour la fonction de réinitialisation du mot de passe.

Dans l'ensemble, l'application a respecté les principes de conception des applications mobiles et les lignes directrices de développement, avec un contraste de couleurs, une lisibilité et une présentation appropriés. En outre, les journaux de l'asthme et de la BPCO, les profils de médication et les plans d'action ont été élaborés sur la base de lignes directrices validées cliniquement. Ces étapes sont essentielles pour répondre aux normes industrielles et préserver la crédibilité, l'accessibilité et la convivialité de l'application. Les prochaines étapes consisteront à étendre la compatibilité de l'application à des cadres multiplateformes afin d'améliorer l'accessibilité et l'équité de l'application.

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I thank Lisa Martignetti for her incredible assistance in the IRB application, managing administrative and financial aspects of the project, Aaron Glick for his time and advice in brainstorming the initial ideas for the app, and Meghana Munipalle and Romi Bonomo for their assistance in pilot testing the app. I am also grateful to the members of VUA lab at McGill who provided me with feedback to improve my research skills.

I would also like to dedicate this thesis work to my Parents, Aunt Estella, Uncle Mark, Sister Emily for your endless encouragement via countless phone calls. You taught me that anything is achievable with perseverance. Thank you very much for believing in me.

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Contribution of Authors

U San Chao: Conceptualization (equal), Investigation (lead), Development (lead), Software (lead), Methodology (equal), Formal Analysis (equal), Data Curation (equal), Writing–original draft (lead).

Nicole Li-Jessen: Supervision (lead), Conceptualization (equal), Funding Acquisition (lead), Resources (lead), Methodology (equal), Formal Analysis (equal), Data Curation (equal), Writing–review and editing (lead).

Lisa Martignetti: Writing – Review & Editing (Supporting)

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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
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

Chapter 1: Introduction

1.1 Project Overview

Asthma and chronic obstructive pulmonary disease (COPD) are the most common chronic respiratory diseases that require continuous disease monitoring and management.[1,2] In Canada, an estimated 3.8 million people have asthma, and 2 million people have COPD.[3] Asthma and COPD symptoms (e.g., coughing, wheezing etc.) can worsen due to a variety of triggers such as exposure to environmental conditions (e.g., weather, pollen etc.). Poor symptom control and frequent exacerbation can become life-threatening and lead to an increase in hospitalization and costs. Telemonitoring is a common remote monitoring tool for asthma and COPD but typically have used only in patients who have already experienced severe symptoms, frequent exacerbations, and multimorbidity.[4] In addition, the result of telemonitoring significantly depends on clinician–patient relationships and communication technologies to adequately identify the disorders, and often daily symptoms and fluctuations may not be reported.[5]

Mobile health (mHealth) apps are software and digital platforms that operate on a smartphone or tablet and can be used to process and view the digital signals obtained from wearable devices.[6] Wearable devices and mHealth app technology can help control asthma and COPD symptoms through continuous real-time monitoring of lifestyle and weather conditions and early detection of exacerbations.[7] Many wearable devices use audio sensing technology to detect audible symptoms (e.g., cough, wheeze etc.) associated with asthma and COPD and smartphones to collect/analyze the audio data. However, with wearables that use acoustic microphones, their audio signals carry identifiable speech information and personal privacy becomes a significant concern. In addition, computing capacity on a smartphone alone has shown to be maxed out rapidly with the detection of one single symptom due to the complexity of audio signals.

To address the privacy concern, Dr. Li-Jessen's team has developed a wearable device, namely **AIrway**, based on the neck surface accelerometer (NSA) technology, to monitor upper airway symptoms. The NSA is a miniaturized sensor placed on the neck surface to detect and transfer the mechanical skin vibrations (transmitted from the vocal folds and vocal tract) to electrical signals.[8] Therefore, instead of collecting microphone-acoustic signals, the NSA captures negligible vocal tract resonance information, which preserves a person's speech privacy. Furthermore, AIrway's machine learning algorithms will be allocated in both the wearable device (for symptom event classification) and the smartphone (for exacerbation prediction) to leverage the computing resources. **Figure 1** described the overall project overview and the specific scope of this thesis.

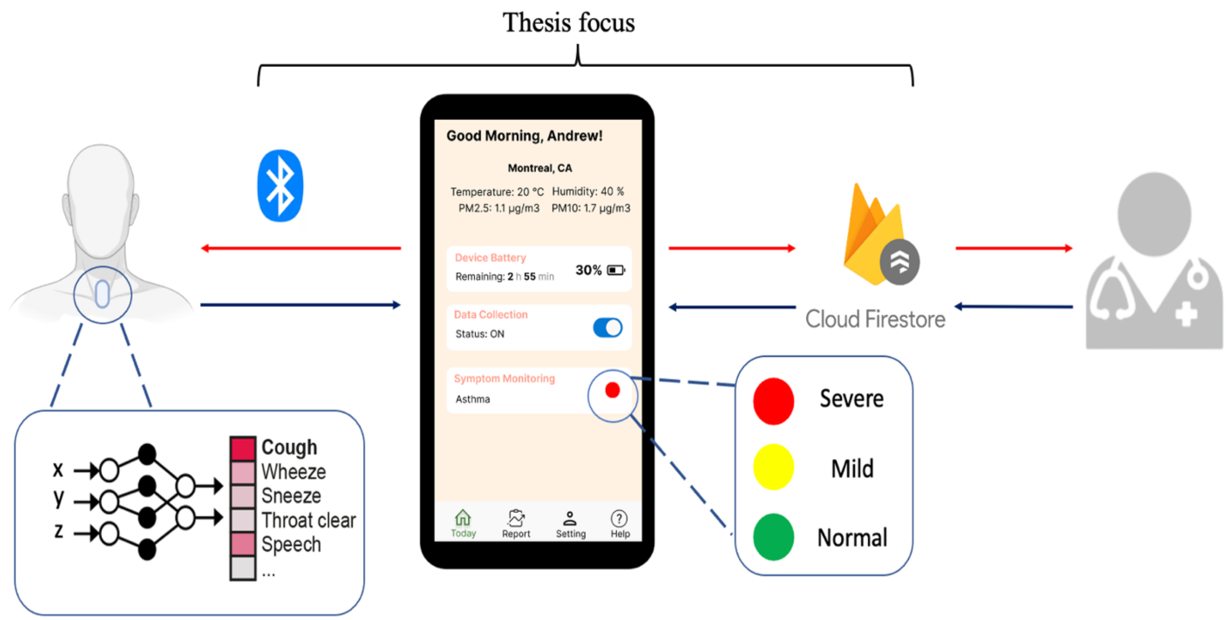


Figure 1. AIrway project overview. This thesis focuses on developing a companion app for the NSA wearable. The App includes features of Bluetooth data transmission, personalized account creation, local weather information retrieval, data visualization, and cloud data storage establishment.

The user-centered mHealth app development steps proposed by McCurdie[9] are illustrated in **Figure 2**. In the scope of this thesis project, the AIrway app is developed by following steps 1-4, namely problem identification (Chapter 1), literature review (Chapter 2), design and development (Chapter 3.2-3.3), and test and evaluation (Chapter 3.4 and Chapter 4.3). The usability study involves two groups: 1) technical raters (i.e., app developers) and end-users (i.e., patients with asthma and COPD). This thesis focuses on gathering feedback from the technical raters, and the feedback from end-users will be collected once the technical revisions of the app have been incorporated. Future directions for the project also include deploying the AIrway app on app stores (step 5).

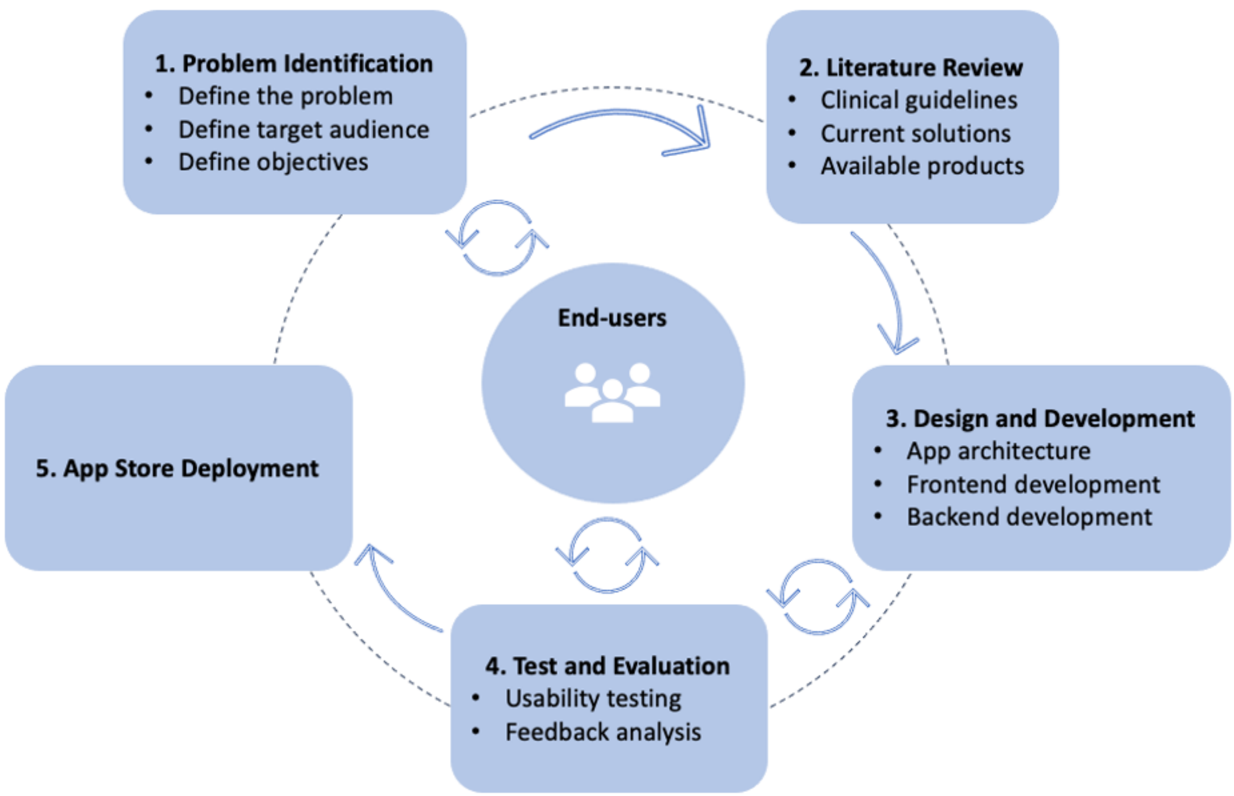


Figure 2. mHealth development process (adapted from McCurdie, T., et al[9])

1.2 Research Objectives

The overarching goal of this project is to develop a wearable device and a mobile application for remote monitoring in patients with asthma and COPD individuals. The wearable device has been developed by a hardware engineer in Dr. Li-Jessen's team. For this master's thesis, the research aims are to 1) design and develop a mobile app to support a wearable device for data collection and visualization (Section 3.2 and Section 3.3), and 2) perform a usability evaluation of the app (Section 3.4). Essential features of the app include the ability to create a personalized user profile, establish a wireless connection with the device via Bluetooth, collect real-time classification of airway symptom data, retrieve local weather information, and predict the user's healthcare conditions.

1.3 Study Significance

The study holds two study significances. First, this thesis represents the first milestone of the technical development of the AIrway app. The app is specifically developed for asthma and COPD self-management functions, such as personalized medication information delivery and clinical diary data collection. It also incorporates mobile app design principles to optimize the app's usability and accessibility. Furthermore, the app is assessed by technical raters, namely app developers, who provided valuable feedback about the app's functions and user interfaces. The feedback will be used to guide the upcoming revision of the app before it is made available to clinical populations, i.e., asthma and COPD patients.

Second, this thesis has the potential to bridge the gap in telemonitoring treatment and provides a more effective option for asthma and COPD patients in the future. Specifically, the AIrway app will support the data collection of the NSA device and effectively capture patients' changes in symptoms and frequent exacerbations while preserving their speech privacy. This capability will be beneficial for both patients and healthcare providers, as it can enhance early detection of the disease and enable early intervention.

Chapter 2: Literature Review

This section is organized to review the literature on (1) asthma, (2) COPD and (3) existing commercial wearable devices and apps for asthma and COPD remote monitoring. As the AIrway is designed for adult patients at this moment, the focus of the literature review will be on adult populations.

2.1 Asthma

The Global Initiative for Asthma (GINA) defines asthma as "*a common and chronic inflammatory disorder of the airways. This inflammation causes recurrent episodes of coughing, wheezing, breathlessness, and chest tightness. These episodes are usually associated with widespread but variable airflow obstruction that is often reversible either spontaneously or with treatment.*"[10] Asthma can occur at different life stages, including childhood, adolescence, and adulthood due to various factors. The details of prevalence, symptoms, pathophysiology, etiology and risk factors, and management are described below.

2.1.1 Prevalence

Asthma affects more than 300 million people worldwide, with a higher prevalence commonly found in Western countries with a high gross domestic product.[1] The World Health Survey collected data on the prevalence of clinical asthma in adults and found that higher prevalence in developed countries, such as Australia (21.5%) and Canada (12.08%), and lower rates in developing countries, such as China (1.4%) and Vietnam (1.0%).[11-13] This prevalent difference could be attributed to factors such as pollution, lifestyles, and rates of obesity.[13] Additionally, the US National Health reported that asthma is more prevalent among females, non-Hispanic black populations, and low-income households.[14] In Canada, approximately 500 adults die annually and annual direct costs per person are about CAD$1,000 due to asthma.[3,15]

2.1.2 Clinical Symptoms

The primary symptoms experienced by asthmatics are wheezing, shortness of breath, coughing, and chest tightness. These symptoms tend to worsen at night or in the morning.[16] They can occur individually or in any combination at the same time.

In clinical settings, terms such as asthma attacks, episodes, flare-ups, or exacerbations are often used to describe the acute conditions experienced by patients with worsening asthma symptoms.[17] Asthma exacerbations are a significant cause of mortality, hospitalization, and healthcare costs.[10] Patients with severe asthma can experience at least one exacerbation per week.[17]

2.1.3 Pathophysiology

The underlying pathophysiology of asthma is primarily due to airway inflammation.[18] Normally, the lungs have two bronchi that facilitate the airflow in and out of the body. The airways also have a layer of smooth muscles that enable them to expand or constrict. When the body needs higher demand for oxygen (e.g., during exercise), the airways will expand to accommodate the airflow.

When air pollutants get inhaled, the immune cells (e.g., mast cells) release inflammatory mediators, such as cytokines and histamine, in response to these unwanted pollutants.[19] Consequently, these mediators contract the smooth muscles leading to airway constriction and preventing the pollutants from passing through. This constriction, clinically known as bronchoconstriction, increases the workload of breathing and gives rise to asthma-related symptoms, such as shortness of breath.[20] Furthermore, asthmatic airways are more sensitive to external stimuli. As a result, an exaggerated bronchoconstriction can occur which is known as airway hyperresponsiveness.[20]

2.1.4 Etiology and Risk Factors

The exact cause of asthma is believed to be a multifactional condition affected by genetics and environmental factors.[18] Generic studies have shown heterogeneity in asthma, but no specific gene has been identified yet for asthma development.[16] That said, it is clear that a family history with a genetic predisposition relating to allergies or atopic dermatitis increases the likelihood of asthma development because genetics can affect airway responsiveness to external triggers or stimuli (Section 2.1.3).

Asthma exacerbations can be triggered by various factors including exposure to external agents, poor symptom control and inadequate medication adherence.[17] There are three types of common risk factors that asthmatics should avoid: inflammatory factors, irritants, and lifestyle factors.[1,10] Inflammatory factors include allergens (e.g., pollen, cockroach allergens, and animal hairs etc.) and respiratory infections (e.g., viral upper respiratory tract infection). Irritants include cold, temperature change, strong odours, stress and emotions. Lifestyles include tobacco smoke, medications, and food additives.

2.1.5 Clinical Management

To achieve effective asthma management, it is important to consider both current control and future risk reduction (**Figure 3**).[21] For assessing current asthma control, a patient's levels of symptoms, reliever use, daily activity, and lung function status are considered clinically. Self-reported and clinically validated questionnaires are commonly used to assess these patient factors before and after an intervention and to predict exacerbation in clinical practice. For example, one study used the Asthma Control Test (ACT)[22] questionnaire in 3000 asthmatic patients and predicated partly controlled (mild) or uncontrolled (severe) asthma with an accuracy of 94% over a period of 4 weeks.[23]

For future risk reduction, long-term management of worsening symptoms, lung function loss, medication adverse effects, and exacerbations are considered clinically. Healthcare providers collaborate with patients to develop a personalized action plan that guides their drug regimen and prompts immediate action during exacerbations.[24] Studies have shown that a written action plan supported by a healthcare provider detected exacerbations 1.7-6.5 days before onset and encouraged 50% more patients to self-treat their exacerbation with antibiotics and prednisone.[25,26] Overall, the combination of clinical questionnaires and action plans has shown effectiveness in predicting future risks and managing exacerbation.

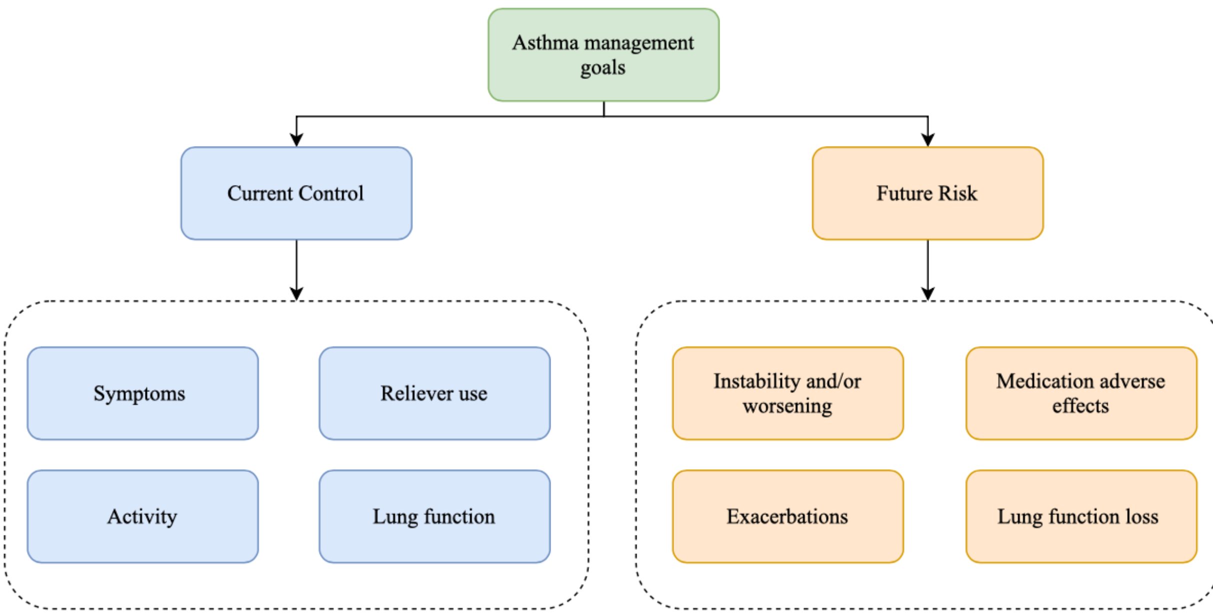


Figure 3. Asthma management goals (adapted from Bateman, E.D et al[21]).

2.2 Chronic Obstructive Pulmonary Disease (COPD)

The Global Initiative for Chronic Obstructive Lung Disease (GOLD) defines COPD as "*a heterogeneous lung condition characterized by chronic respiratory symptoms (dyspnea, cough, sputum production and/or exacerbations) due to abnormalities of the airways (bronchitis, bronchiolitis) and/or alveoli (emphysema) that cause persistent, often progressive, airflow* *obstruction.*"[27] The details of prevalence, symptoms, pathophysiology, etiology and risk factors, and management are described below.

2.2.1 Prevalence

An estimated 328 million people have COPD worldwide, making it the third leading cause of death.[28] Countries with low income, such as the Philippines (20.8%), have higher COPD mortality rates than high-income countries, such as Canada (9%).[29-31] Systematic reviews found strong evidence that the prevalence of COPD is higher among smokers, individuals aged 40 years and above, and men.[32,33] In Canada, the mortality rate is 4.4% and annual direct costs per person are about CAD$2,000 due to COPD.[3,34]

2.2.2 Clinical Symptoms

The primary symptom that characterizes COPD is chronic dyspnea, followed by cough with sputum production.[29] Wheezing, chest tightness, and fatigue are also common and persistent symptoms that COPD patients experience. These symptoms are particularly troublesome during awakening for patients and the frequency can vary depending on their severity conditions.[35] Furthermore, the main symptoms of COPD exacerbations are typically associated with an increase in dyspnea, sputum, and cough, and these exacerbations can last anywhere from several days to 12 weeks.[28]

2.2.3 Pathophysiology

The main pathophysiological features of COPD are obstructive bronchiolitis and emphysema.[28] During inhalation, the air moves through two tubes (i.e., bronchi) and the bronchi which are smaller tubes that contain elastic alveoli. The alveoli fill up with the air and provide oxygen to the blood.[36] In patients with COPD, their airways are inflamed and narrowed and can produce excessive mucus in bronchial tubes, which can block the airways. This process is known as obstructive bronchiolitis and it contributes to the chronic cough experienced by the patients.[37]

In addition, in COPD, the alveoli become damaged and lose their elasticity. As a result, the air is trapped, and the lungs cannot easily deflate during exhalation. This can cause difficulty in breathing and contributes to the shortness of breath experienced by the patients. This process is known as emphysema.[38] These pathophysiological changes contribute to the characteristics and clinical symptoms observed in patients with COPD.

2.2.4 Etiology and Risk Factors

The most well-established risk factor for COPD development is tobacco smoking.[29] Occupational exposure, air pollution, and genetics are also common COPD risk factors.[39] Occupational exposure can occur due to dust, chemical agents, and fumes. Particularly, professions such as farmworkers, vehicle mechanics, and material-moving operators, have a high likelihood of being exposed to these substances in their workplace.[40] Air pollution, including biomass fuel and wood-burning stoves, is another significant factor. Both occupational exposure and air pollution are the main causes of airway limitation and obstructive bronchiolitis. Furthermore, hereditary alpha1-antitrypsin deficiency is a genetic disorder that contributes to lung diseases, including COPD. This deficiency results in the loss of control of neutrophil elastase, leading to alveoli destruction and causing emphysema.[41,42]

2.2.5 Clinical Management

The most effective intervention for COPD is smoking cessation, which can increase lung functions and reduce mortality rates.[39] Management of COPD includes symptom reduction and risk reduction using non-pharmacological and pharmacological treatment (**Figure 4**). The specific pharmacological treatment depends on the severity of the COPD patients. Clinically validated COPD questionnaires are used to assess COPD severity levels and exacerbations.[29] For example, one study used the COPD Assessment Test (CAT) questionnaire with a total of 140 COPD patients and found that the CAT was able to capture mild and moderate exacerbations over 15 months with

82.4% accuracy.[43] Another study has also shown that a written and personalized COPD action plan with proper instructions for exacerbation management led to a reduction of 5 days in total recovery time.[44] Overall, the use of COPD clinical questionnaires and action plans enhances self-management support for patients.

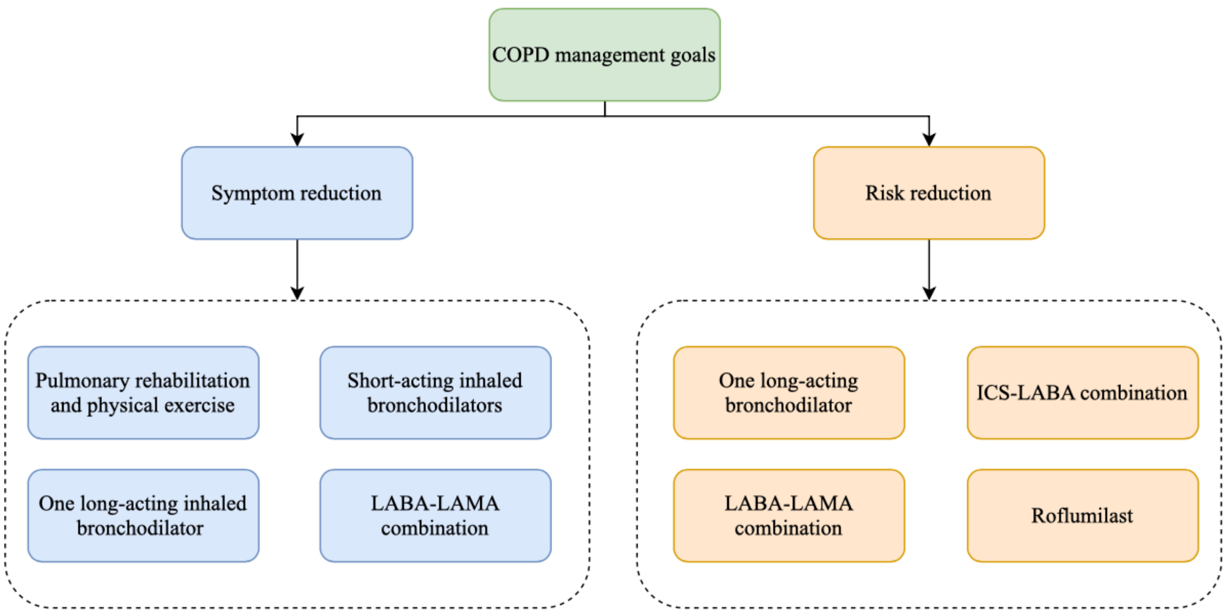


Figure 4. COPD management goals (adapted from Peter J.B et al[28]). ICS, inhaled corticosteroid. LABA, Long-acting beta-agonists. LAMA, long-acting muscarinic antagonist.

2.3 Use of Wearable Device for Remote Airway Health Monitoring

2.3.1 Telemonitoring: Benefits and Limitations

Telemonitoring, also known as telemedicine, is defined as "*the use of audio, video, and other telecommunications and electronic information processing technologies to monitor patient status at a distance.*"[45] Telemonitoring has been used in various clinical settings to monitor an individual's blood pressure, respiratory rate, and glucose level for cardiovascular, respiratory, and diabetic diseases.[46]

Telemonitoring has proven beneficial for management outcomes and cost reduction by overcoming physical and transportation barriers.[47] For instance, one study highlighted the implementation of a telemonitoring program for COPD patients, resulting in a reduction of hospitalizations by more than 50% and saving CAD $355 per patient over a 6-month period.[48] However, the effectiveness of telemonitoring in asthma and COPD patients has primarily been found beneficial to those who have already experienced severe symptoms, frequent exacerbations, and multimorbidity.[4] In addition, successful telemonitoring outcomes significantly depend on the communication technologies employed. It is noted that daily symptoms and fluctuations may not always be accurately reported through telemonitoring systems.[5] For instance, the 2021 Telehealth Survey Report revealed that 76% of patient data (e.g., blood pressure) was not collected or reported via communication technologies (e.g., audio and video calls).[49] Furthermore, telemonitoring imposes an additional burden on clinicians. One study found that synchronous telemonitoring visits during the COVID pandemic increased the average time spent on each patient by 2.5% in 2021.[50] This increased workload can potentially lead to medical errors or misdiagnoses. Overall, telemonitoring is not the most effective method for remote monitoring of asthma and COPD conditions.

2.3.2 Wearable Device Technology

Wearable devices are widely used in healthcare for remote monitoring of chronic diseases and postoperative rehabilitation because of the hardware capacity and affordability.[51] These devices are equipped with miniature biosensors, flexible materials, and wireless communication modules to capture an individual's physiological data, such as heart rate and skin temperature. These devices are typically placed on specific body parts to collect the data, which is then transmitted to a computer or smartphone platform for data visualization or analysis.[52] A local or cloud database, such as Microsoft Azure[53] and Google Firebase Firestore,[54] is often incorporated to facilitate data storage.

Previous studies have used wearable devices to control asthma and COPD symptoms through continuous real-time monitoring of lifestyle and environmental conditions and early detection of exacerbations.[7] Many wearable devices use audio sensing technology to detect audible symptoms (e.g., cough, wheeze etc.) associated with asthma and COPD and smartphones to collect/analyze the audio data. However, acoustic signals carry identifiable speech information and personal privacy is a significant concern with wearables that use microphone-acoustic signals.

To address the privacy concern, Dr. Li-Jessen's team has developed a wearable device, namely **AIrway**, based on the neck surface accelerometer (NSA) technology, to monitor voice and upper airway symptoms. The NSA is a miniaturized sensor placed on the neck surface to detect the skin vibration transmitted from the vocal folds and vocal tract. NSA-derived biomarkers (e.g., sound pressure level and jitter) have shown similar acoustic results compared to acoustic microphones and successfully identified changes in the deterioration of vocal functions.[55] However, there is currently no user interface (e.g., a mobile app) or cloud database available for visualizing and storing the NSA data. As a result, users do not have access to the necessary data for taking actionable steps to self-manage their asthma and COPD conditions. These limitations motivate the development of a mobile health app to support the NSA data visualization and storage, allowing users to effectively monitor their conditions.

2.3.3 Mobile Health (mHealth) Apps

The World Health Organization defines mobile Health (mHealth) as "*medical and public health practice support by mobile devices, such as mobile phones and other wireless devices.*"[56] mHealth apps have been used to collect an individuals' health data via smartphones and tablets to allow healthcare providers to monitor their patients' condition outside clinical settings.[57] These apps can be used independently or paired with wearable devices to facilitate data collection and visualization. Studies have shown that mHealth apps can increase medication adherence by 50% through alerts and reminders and improve the level of disease-related knowledge by 52%.[58]

2.3.4 Airway mHealth Product Comparison

Commercial wearable devices and mHealth apps designed for activity monitoring and asthma/COPD management were reviewed herein. The search was conducted on Apple App Store, Google Play Store, and Google Scholar using keywords "wearable devices", "mHealth apps", "asthma", and "COPD" in December 2021. Three types of systems were found available on market (**Table 1**).

The first type involves the combination of a smartwatch device (e.g., Apple Watch[59] and Fitbit[60]) with a corresponding app. These smartwatches are equipped with a wide range of biosensors (e.g., accelerometer and temperature sensors) to capture an individual's physiological data. The collected data is then displayed on the app for data visualization.

The second type utilizes a customized wearable device (e.g., Afflo[61]) paired with an app. In this case, a microphone module is incorporated into the wearable device to collect an individual's audio samples, and machine learning algorithms are used to predict asthma outcomes based on the classification of the samples. Similarly, the app is used to display the relevant results.

The third type involves a standalone app (e.g., Breathe[62] and Sonde Health[63]) that incorporates either a chatbot or a clinical questionnaire. The app utilizes these interactive features to predict an individual's respiratory outcomes based on the individual's inputs. This type does not include wearable devices or external sensors for data collection.

Table 1. Review of commercial wearable devices and apps.

Product	Type	Hardware	Data Acquisition	Data Visualization
Apple Watch[59]	Smartwatch paired with an Android/iOS app	Blood oxygen sensor, heart rate sensor,	Physiological signals based on sensors via Bluetooth	Fitness tracking, step count, blood oxygen level, sleep patterns

		accelerometer, gyroscope		
Fitbit[60]	Smartwatch paired with an Android/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[61]	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 wearable device via Bluetooth. Use of APIs to retrieve air pollution, and medications	Use of AI to predict asthma outcomes Air pollution, pollen, medications
Breathe[62]	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[63]	A standalone iOS and Android app	Use smartphone microphone to collect voice sample	User questionnaire (symptoms), voice sample (e.g., say "ahhh" for 6 seconds	Respiratory score (0 - 100)

2.4 Research Gaps

Traditional telemonitoring is useful but not the most effective method for remote monitoring of asthma and COPD conditions. Wearable devices and mHealth apps provide a promising alternative to support the clinical management of asthma and COPD symptoms by promoting patient self-management. However, some devices and apps rely on microphones for data collection, which raises privacy concerns. The proposed NSA will address privacy concerns by collecting unidentifiable acoustic signals that represent airway symptoms. Currently, the NSA lacks a companion app for data visualization and cloud data storage. Therefore, this thesis project is a part of the technical development of the broad AIrway project, aiming to develop an app to facilitate NSA data visualization and cloud data storage.

Chapter 3: Methodology

This section is organized as (1) app architecture (2) frontend development (3) backend development and (4) a usability study for the AIrway mobile app evaluation. The background and rationales underlying each design and function element of the app are described below.

3.1 App Architecture

The AIrway app was developed in Android Studio (Chipmunk 2021.2.1 version).[64] The architecture principles from the Android development guidelines[65] were used to guide the frontend (e.g., data visualization) and backend (e.g., data storage) development in this project. Also, according to the guideline, each app should have at least two layers: the User Interface (UI) layer and the data layer (**Figure 5**). The UI layer is responsible for user interaction and data presentation on the app screen, while the data layer is responsible for implementing the app logic or database establishment running behind the scenes.[65]

In the AIrway app, the frontend development included designing visual layouts of the interfaces and navigations, creating user input fields, and implementing notifications to interact with users (e.g., clinical diary completion). Meanwhile, the backend development included storing and retrieving user data of the account information and clinical diary response, transmitting data between a cloud database and the app. Specific protocols for frontend and backend development are described in Section 3.2 and Section 3.3, respectively.

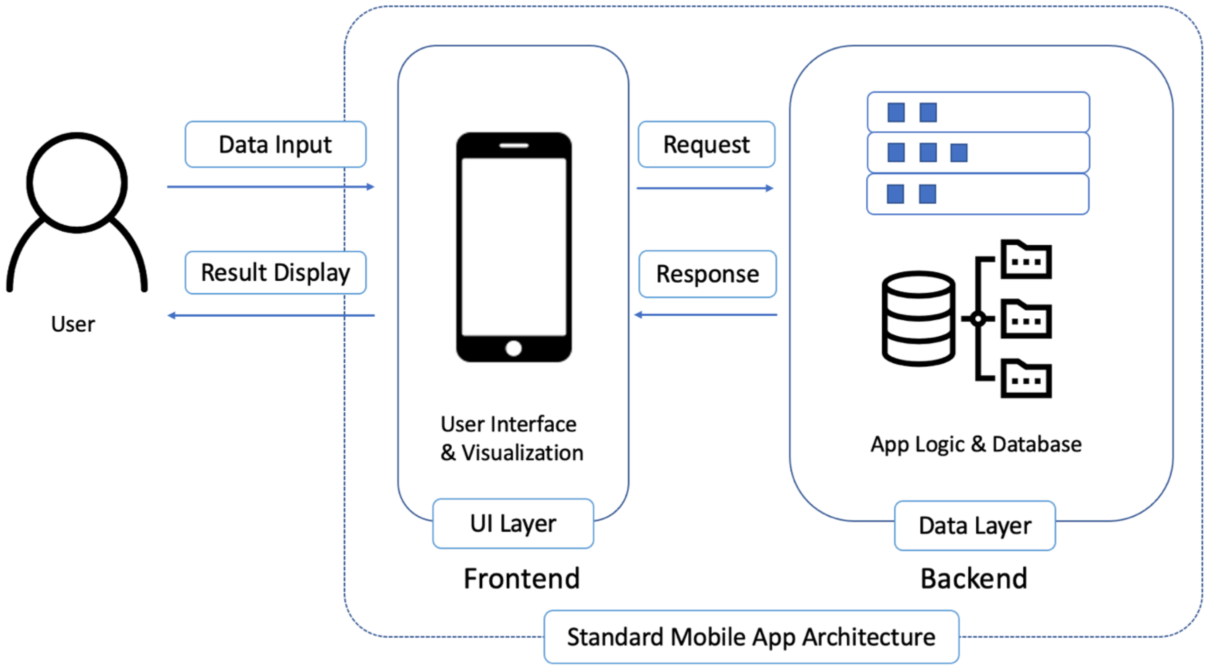


Figure 5. A standard app architecture (adapted from Android Developers Documentation[65,66]).

3.2 Frontend Development

The frontend development used XML (eXtensible Markup Language – version 1.0),[67] which is the default language in Android Studio (Chipmunk 2021.2.1 version)[64] for creating app interfaces. Frontend development is the process of creating User Experience (UX) and User Interface (UI) in website and mobile applications.[68] UX is the physical interaction between users and applications, such as navigation and input methods. On the other hand, UI focuses on the visual appearance of the applications, such as the layouts or colours of the texts displayed on the screen.[69]

3.2.1 Design Principles

Morville's design principles[70] were adopted to guide the UX and UI design of the AIrway app (**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 elderly[71] and a post-traumatic stress monitoring app.[72]

For this project, the end users are individuals with asthma or COPD, who are often elderly. To apply Morville's principles for the AIrway app, the UX and UI were built with simplified user interfaces, large texts, easy-to-use navigation buttons, and motivational functions, such as goal settings and reminders to keep users engaged and encouraged for continued usage.[73]

Table 2. Adaptation of Morville's design principles for the AIrway app.

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 and emergency contact. 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 in collaboration with researchers at the University of Erlangen-Nuremberg. 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,[60] Afflo,[61] and Breathe[62]). The clinical diary and prediction results were developed based on clinical guidelines and literature (such as GINA[74] and GOLD[29]).
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)[75] 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 in Chapter 3.4 and the responses were summarized in Chapter 4.

Usability	Q7: How easy and satisfying is it to use the app? • A usability study was conducted with app developers. The study protocol was outlined in Chapter 3.4 and the responses were summarized in Chapter 4.

3.2.2 UX and UI Design Considerations

3.2.2.1 Optimal Element Layout and Text Font Size

One aim here is to deploy the AIrway app across different devices, such as LG, Google Pixel, and Samsung, that use the Android operating system. As these devices can vary significantly in their screen size, the app content display can be significantly altered, and information may become misaligned. To address this development issue, the AIrway app UI was built using the constraint layout[76] based on the Android Material Design Guidelines.[77]

Constraint layout is a layout style that applies to UI elements (e.g., buttons and texts) and controls how the elements are positioned relative to each other. For instance, the elements can be specified always relative to the top, center, or bottom of the screen using constraint layout in the XML (version 1.0)[67] file.[76] As such, the AIrway UI components were flexible to adjust and fit different screen sizes. Also, according to the Android Guidelines,[77] interface titles should be a minimum of 20sp (scalable pixels), a subtitle should be 16sp, and buttons and body should be text 14sp to facilitate readability and enhance the user's visual experience. These recommendations were followed when building the AIrway app.

3.2.2.2 Optimal Colour Contrast for App Interfaces

Colour contrast is critical in UX and UI mobile app design as it can affect user accessibility and usability. According to Web Content Accessibility Guidelines (WCAG),[75] the visual presentation of 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. To meet WCAG standards, the colour contrast of the AIrway app UI components, including the background and button colours, was fine-tuned using an open-source colour contrast checker[78] to achieve a well-balanced design (**Table 3**).

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

3.2.2.3 Literacy Analysis for App Written Materials

To ensure that the AIrway app's written materials were easily understandable, an open-source readability calculator, Online-Utility.org,[79] was used for literacy analysis before implementing into the app UI. The written materials included the privacy policy, frequently asked questions (FAQ), the asthma action plan, and the COPD action plan. The target level was set at a grade 9 level, which was the reading level of most English-educated adults in the United States.[80]

The Flesch Reading Ease Score[81] 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.[82] 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.[82] The written materials of the app were iteratively revised to meet the target grade 9 level without compromising the information.

Based on the readability calculator,[79] 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. Overall, with a score close to 60, it indicated that users with a formal education level of grades 9-10 could use the app with ease.

Further analysis was also performed on the written materials using other metrics for cross-validation, which will be presented in the Result Chapter (Section 4.1). The definitions of all metrics used in this study are summarized in **Table 4**.

Table 4. Readability metrics and definition.[82]

Readability Metrics	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.

3.2.3 App Design Flowchart and UI Design Planning

To set up the user profile, the AIrway app contained several important user interfaces, namely Login and Registration, Location Permission, Account and Emergency Contact Information, Medication, Diary Reminder, and Clinical Diary (**Figure 6**). The specific feature of each interface will be described in Section 3.2.4. In brief, the Login and Registration interface allowed users to input their login information and create an account. The Location Permission interface allowed users to turn on/ off the device's location for parsing local weather information. The Account and Emergency Contact interface allowed users to complete the profile setup and fill out emergency contact information for use in severe events.

The app also contained four main user interfaces: Today, Report, Profile, and Help, mostly for data visualization and information delivery. The Today interfaces displayed the local weather information and the recommended asthma or COPD action plan. The Report interface showed a summary of the data in a graphical format. The Profile interface updated the user account information, such as password, date of birth, and health status (e.g., weight and height). The Help interface provided frequently asked questions, a privacy policy of the app, and a description of the researchers in this project.

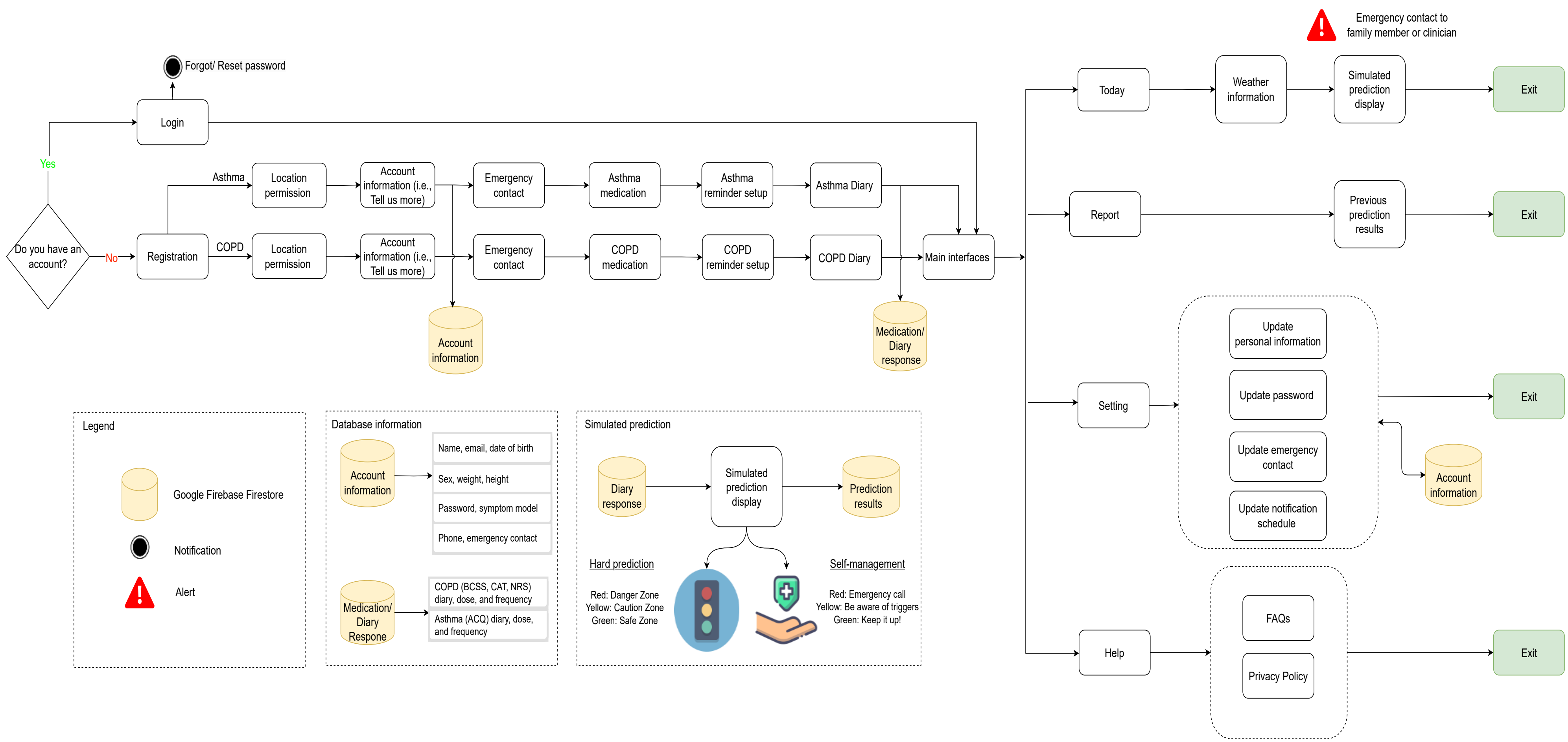


Figure 6. AIrway app design flowchart.

3.2.4 App Interface Implementation

The user interfaces mentioned in Section 3.2.3 were prototyped using an online design tool, namely Figma,[83] before the final UI implementation in the app. Once the design was finalized, the AIrway UI was programmed into a smartphone using XML (version 1.0)[67] in Android Studio (Chipmunk 2021.2.1 version),[64] a Google native Android development integrated development platform (IDE) for the development of Android-related applications. The IDE allowed developers to build Android applications on Windows, Mac, and Linux operating systems. In addition, the IDE assisted developers to build, debug, and test the app from scratch.[84] Android Studio features[85] are summarized in **Table 5.**

Table 5. Android Studio features.[85]

Android Studio tools	Descriptions
Android Software Development Kit (SDK)	• Android SDK is a collection of developments tools and (Application programming interfaces) APIs such that the developers can program and access the device features.
Emulators	• The emulators are virtual devices that consist of predefined configurations and almost all the capabilities of a real Android device, tablet, Wear OS and Android TV emulators.[86]
Android Package Kit (APK)	• In Android Studio, developers can convert their final version of the app into APK files, which are the compressed version of the app. Developers can use the APK file to distribute their app or submit the app to Google Play Store.[87]

3.2.4.1 User Login and Registration

The user first interacted with the Login interface when opening the app (**Figure 7a**). Users would be able to log in with their registered email and password. For those without an account, they would click "*New User? Click Here*" to register a personalized account by entering their full name, email, and password, and selecting a condition to be monitored on the Register interface (**Figure 7b**). Specifically, the email input field was set with validation checks to ensure the entered texts were in a valid email format. The password field was set so that the entered numbers or characters would be displayed as dots to keep the password safe (**Figure 7c**). The condition selection was designed using a drop-down menu, which included "*Asthma*" or "*COPD*." Based on the condition, the app brought users to the specific asthma or COPD related interfaces.

If users forgot their password, they could click "*Forget Password? Click Here*" and a prompt would be shown allowing them to enter a valid email to receive the password reset link (**Figure 7d**). After resetting the password, users could log in with the new password.

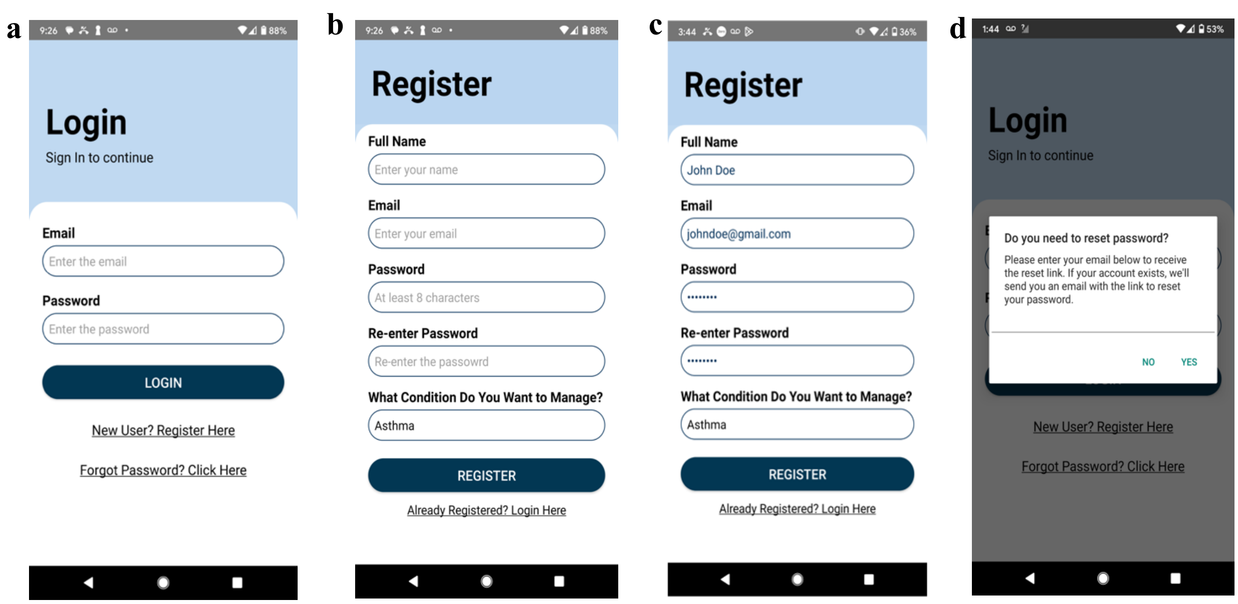


Figure 7. a) Login interface b) Register interface c) Register interface with filled information d) Forgot password prompt.

3.2.4.2 Location Permission

After registration completion, the app asked users if it could access the device's location (**Figure 8a**). The permission was needed to allow the app to retrieve local weather information, which was also explained in the interface (**Figure 8b**). The location permission was declared in the *AndroidManifest.xml* file (i.e., a configuration file for access controls) in **Code 1**.

```
<manifest xmlns:android="http://schemas.android.com/apk/res/android"
   package="com.example.AIrway">
 <uses-permission android:name="android.permission.ACCESS_COARSE_LOCATION"/>
</manifest>
```

Code 1. Location permission declaration in AndroidManifest.xml

This implementation with *ACCESS_COARSE_LOCATION* enabled the app to access only the approximate location of users without storing it.[88] In addition, the app only generated the location permission at runtime and asked users to choose whether to grant permission with three options: "*While using the app*", "*Only this time*", or "*Deny*."

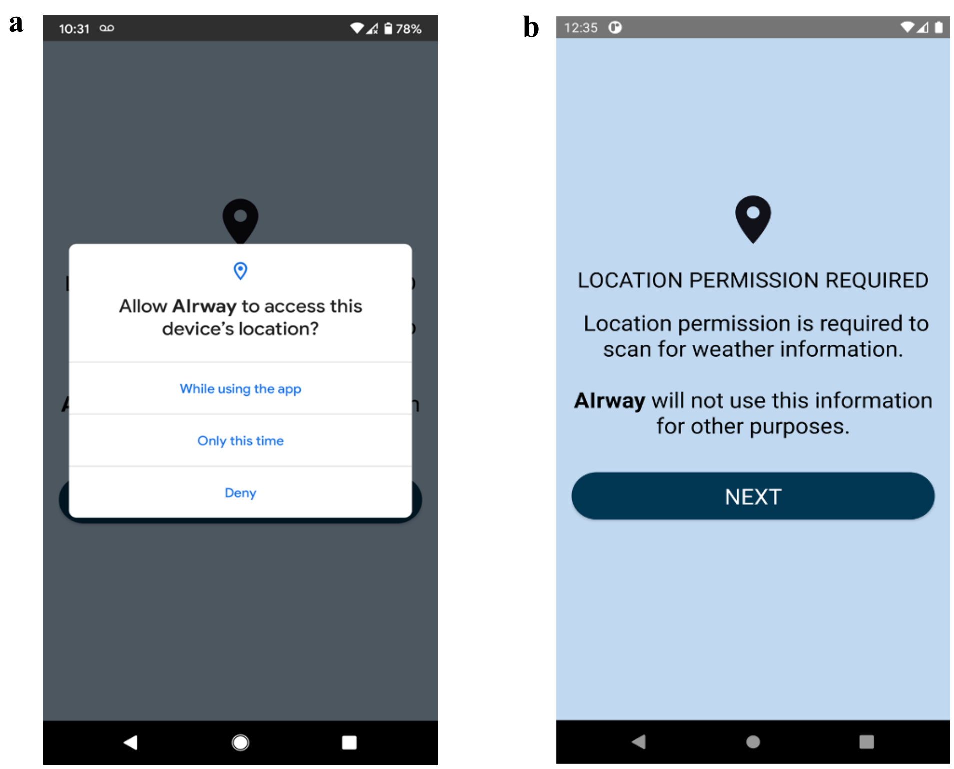


Figure 8. a) Location permission prompt b) Location permission interface.

3.2.4.3 User Account and Emergency Information

The app required users to provide personal information including their biological sex, date of birth, weight, and height (**Figure 9a**). The user input for the category of biological sex was a drop-down menu with three options: "*Male*", "*Female*", and "*Prefer not to say*." For their date of birth, a *DatePicker*[89] component was implemented so that users could easily scroll to select the proper date, month, and year (**Figure 9b**). For the weight and height, the input fields accepted only numerical values and users could also select the unit of measurement as either "*kg*" or "*lbs*" for weight and "*m*" or "*ft*" for height.

Furthermore, the app asked users to provide emergency contact information including the contact name and phone number (**Figure 9c**). Users would be able to choose whether to call the emergency contact immediately when their symptoms exacerbate, e.g., asthma attacks.

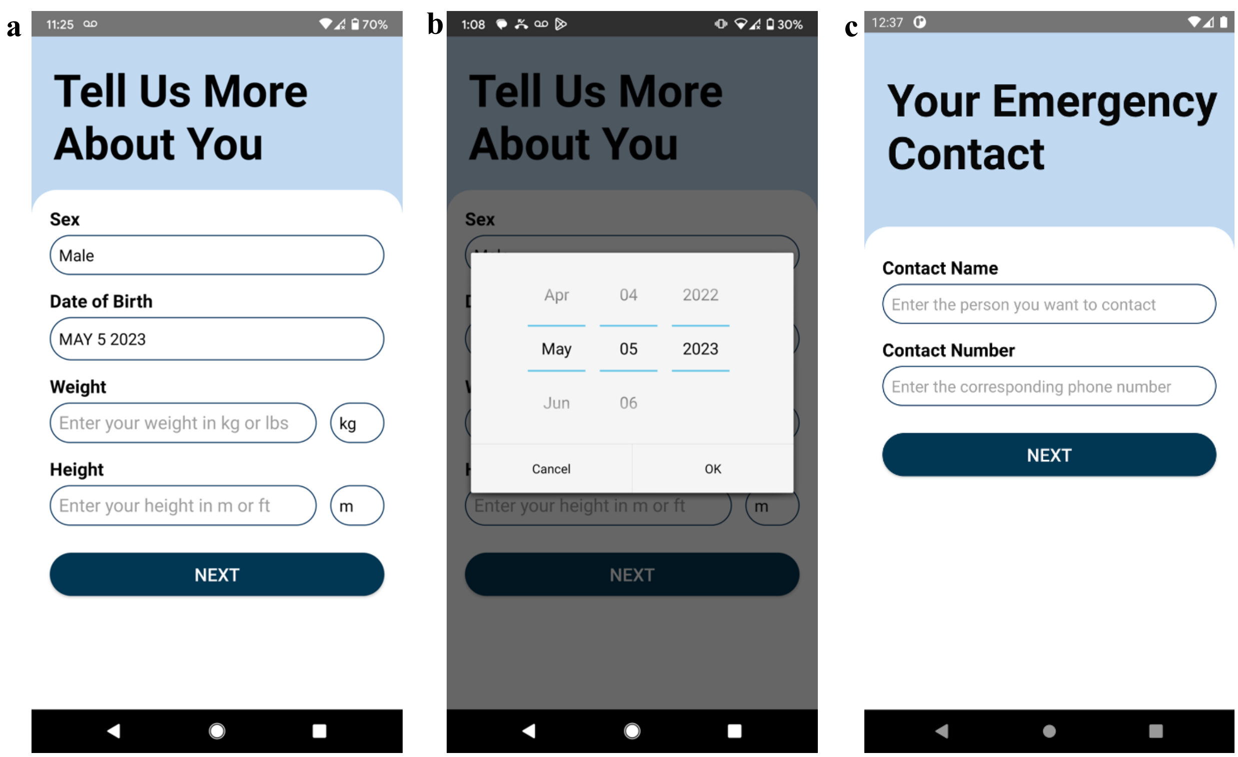


Figure 9. a) Account information interface b) DataPicker selection c) Emergency contact interface.

3.2.4.4 Clinical Medication

Depending on the condition selected during account registration, users were prompted to fill out either the asthma or COPD medication profile including the name, amount, and frequency (**Table 6** and **Table 7**). The design of the medication profile was developed based on the Canadian Lung Association,[90] the Ontario Lung Association,[91] as well as the Breathe app.[62]

Since the medication profile contained more than 10 options, a drop-down menu design was implemented to incorporate the medication profile information. This design prevented cluttering the UI layout with lengthy texts and eliminated the need to navigate through multiple interfaces (**Figure 10**). The design also enabled users to easily select a suitable option by simply clicking the menu. Once an option was selected, the menu would be minimized and only display the selected option, providing a clean and organized UI to users.

Table 6. Asthma medication.

Name	Amount	Frequency
• Advair • Alvesco • Arnuity • Asmanex • Breo • Flovent • Pulmicort • Qvar • Symbicort • Zenhale	• 1 puff • 2 puffs • More than 2 puffs • I don't know	• 1 time a day • 2 times a day • More than 2 times a day • I don't know

Table 7. COPD medication.

Name	Amount	Frequency
• Atrovent • Airomir • Bricanyl • Ventolin • Incruse • Seebri • Spiriva	• 1 puff • 2 puffs • More than 2 puffs • I don't know	• 1 time a day • 2 times a day • More than 2 times a day • I don't know

- Tudorza
- Foradil
- Onbrez
- Serevent

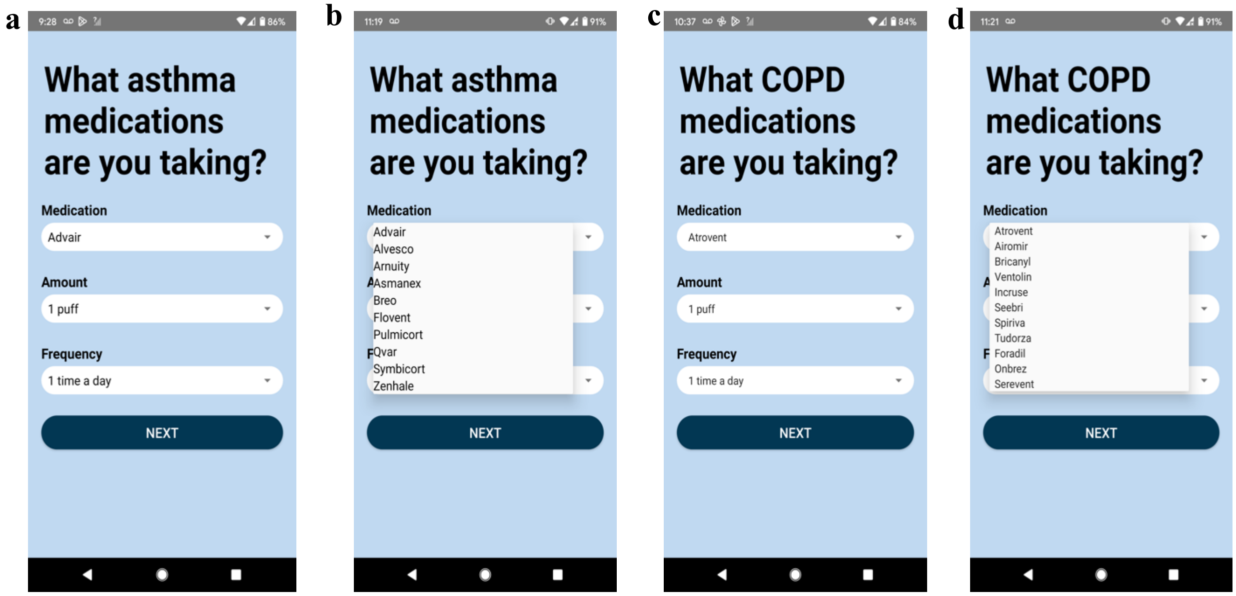


Figure 10. a) Asthma medication interface b) Asthma medication drop-down menu example c) COPD medication interface d) COPD medication drop-down menu example.

3.2.4.5 Clinical Diary

Clinical diaries are a common tool to support patients' self-management and facilitate remote monitoring. In the case of asthma and COPD, effective self-management and improved healthcare outcomes rely on the implementation of clinically validated diaries that are user-friendly, relevant to the patient's symptoms and medications, and capable of identifying the predictors of exacerbations.[92,93]

The selected asthma and COPD clinical diaries met these essential criteria and were integrated into the app (Section 3.2.4.5.1 and Section 3.2.4.5.2). The app was designed to prompt users to fill out the clinical diary (either asthma or COPD) daily in order to support for a more reliable and regular remote symptom monitoring. The prompt occurred either after the initial registration or at the scheduled time.

3.2.4.5.1 Asthma Clinical Diary

The Asthma Control Questionnaire (ACQ)[94] was chosen as the asthma clinical diary in the AIrway app. The ACQ is a clinically validated tool recommended by the Global Initiative for Asthma (GINA)[74] to measure asthma control and change over time. The ACQ was also used in telemedicine applications paired with smartphones for asthma care.[95] The ACQ consisted of five items for assessing asthma symptoms and one item for rescue inhaler bronchodilator usage (**Table 8**).

Table 8. Asthma Control Questionnaire (ACQ).

ACQ questions	**ACQ responses**
Item 1: How often were you woken by asthma during the night?	• Never • Hardly ever • A few times • Several times • Many times • A great many times • Unable to sleep because of asthma
Item 2: How bad were your asthma symptoms when you woke up in the morning?	• No symptoms • Very mild symptoms • Mild symptoms • Moderate symptoms • Quite severe symptoms • Severe symptoms • Very severe symptoms

Item 3: How limited were you in your activities because of your asthma?	• Not limited at all • Very slightly limited • Slightly limited • Moderately limited • Very limited • Extremely limited • Totally limited
Item 4: How much shortness of breath did you experience because of your asthma?	• None • A very little • A little • A moderate amount • Quite a lot • A great deal • A very great deal
Item 5: How much of the time did you wheeze?	• Not at all • Hardly any of the time • A little of the time • A moderate amount of the time • A lot of the time • Most of the time • All the time

Item 6: How many puffs of short-acting bronchodilator have you used today?	• None • 2 puffs • 4 puffs • 8 puffs • 9 - 12 puffs • 13 - 16 puffs • More than 16 puffs

3.2.4.5.2 COPD Clinical Diary

Three COPD questionnaires, namely CAT, BCSS, and NRS were adopted as the COPD clinical diaries for the AIrway app. The COPD Assessment Test (CAT)[96] is recommended by the Global Initiative for Chronic Obstructive Lung Disease (GOLD)[29] for measuring the impact of COPD on a patient's health status and quality of life. The CAT contained eight items that measured the symptom impact of COPD on health status. For example, other researchers developed the MyCOPD app[97] and utilized the CAT to monitor COPD health conditions over 12 months. However, one limitation of CAT is that it may not be sufficient to monitor COPD disease progression on its own.[98]

As such, two additional clinically validated COPD questionnaires: the breathlessness, cough and sputum scale (BCSS)[99] and the numeric rating scale (NRS)[100] were also included to better assess and cross-validate the user's COPD conditions. The BCSS recorded three items: the severity of breathlessness, cough and sputum. The NRS measured one item about the shortness of breath. As a result, the COPD diary in the app consisted of a total of twelve items, summarized in **Table 9**.

Table 9. The breathlessness, cough and sputum scale (BCSS), the COPD Assessment Test (CAT), and the numeric rating scale (NRS) questionnaires.

BCSS questions	**BCSS responses**
Item 1: How much difficulty did you have breathing today?	• None – unaware of any difficulty • Mild – noticeable when performing strenuous activity • Moderate – noticeable even when performing light activity • Marked – noticeable when washing or dressing • Severe – almost constant, present even when resting
Item 2: How was your cough today?	• No cough – unaware of coughing • Rare – cough now and then • Occasional – less than hourly • Frequent – one or more times an hour • Almost constant – never free of cough need to cough
Item 3: How much trouble did you have sputum today?	• None – unaware of any trouble • Mild – rarely caused trouble • Moderate – noticeable trouble • Marked – caused a great deal of trouble • Severe – almost constant trouble
CAT questions	**CAT responses**
Item 4: I never cough	• 0 = I never cough • 5 = I cough all the time

Item 5: I have no phlegm (mucus) in my chest at all	• 0 = I have no phlegm in my chest at all • 5 = My chest is completely full of phlegm
Item 6: My chest does not feel tight at all	• 0 = My chest does not feel tight at all • 5 = My chest feels very tight
Item 7: When I walk up a hill or one flight of stairs I am breathless	• 0 = When I walk up a hill or one flights of stairs I am not breathless • 5 = When I walk up a hill or one flight of stairs I am not very breathless
Item 8: I am not limited doing any activities at home	• 0 = I am limited doing any activities at home • 5 = I am very limited doing activities at home
Item 9: I am confident leaving my home despite my lung condition	• 0 = I am confident leaving my home despite my lung condition • 5 = I am not at all confident leaving my home because of my lung condition
Item 10: I sleep soundly	• 0 = I sleep soundly • 5 = I don't sleep soundly because of my lung condition
Item 11: I have lots of energy	• 0 = I have lots of energy • 5 = I have no energy at all
NRS question	**NRS responses**
Item 12: Indicate how much shortness of breath you are having right now	• 0 = No shortness of breath • 10= shortness of breath as bad as can be

3.2.4.6 Clinical Diary Interface

The asthma diary was developed using the original version of ACQ, while the COPD diary utilized the BCSS, CAT, and NRS (all three were original) (**Figure 11**). The diary questions were presented one per page, with navigation buttons labelled "*Back*" and "*Next*." A progress status bar was also added at the top of the page to indicate which question users were answering.

The clinical diary questions were presented in two styles: $RadioButton$ and $Likert - Scale$. Both styles allowed for single-choice responses. For $the\ RadioButton$ style, users could change their answers by selecting another response. For the $Likert - Scale$ style, users could click on the selected response again for cancellation and choose a new response if they wished. If users forgot or attempted to advance to the next question without selecting a response, a popup message "*Please select one choice*" would appear to remind users to complete the question.

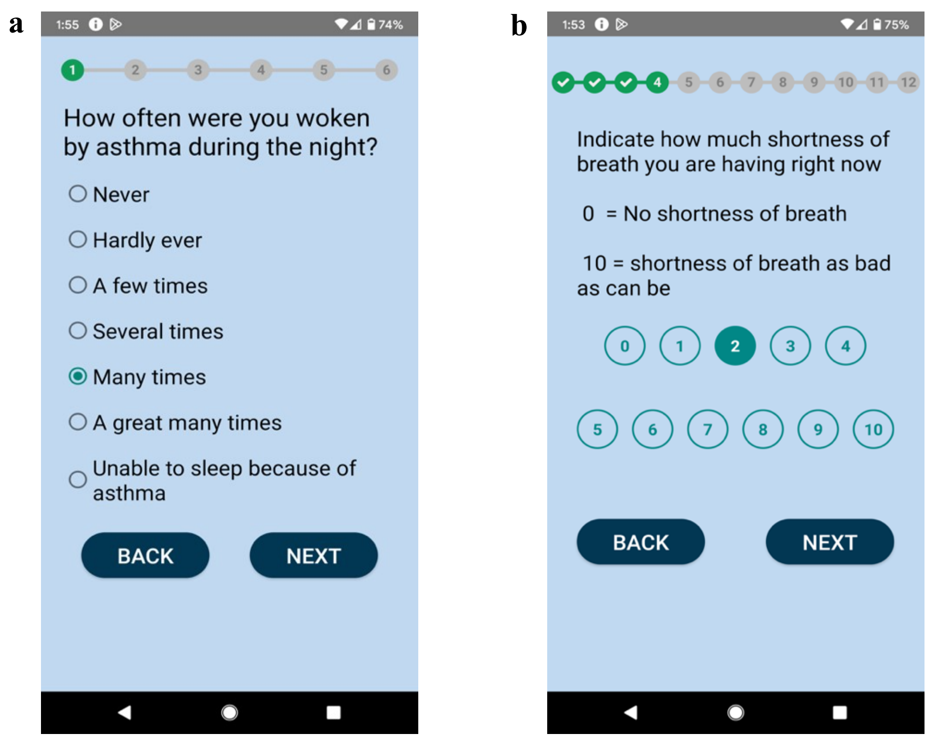


Figure 11. a) An ACQ question is presented in the asthma diary interface b) The NRS question is presented in the COPD diary interface.

3.2.4.7 Clinical Diary Notification

To provide users with flexibility and ensure that they complete the clinical diary each day, a time reminder interface was implemented using the *TimePicker*[101] component (**Figure 12**). This component allowed users to easily scroll the timer and click the "Set" button to schedule a time (a.m./p.m.) for diary completion. At the scheduled time, a corresponding notification prompt would appear in the notification center with the message "*Please complete the diary now!*" The notification included two buttons: "*Complete*" and "*Dismiss*." Clicking the "*Complete*" button would bring users to the corresponding diary (asthma or COPD) for completion while clicking the "*Dismiss*" button would dismiss the notification without requiring further action from users.

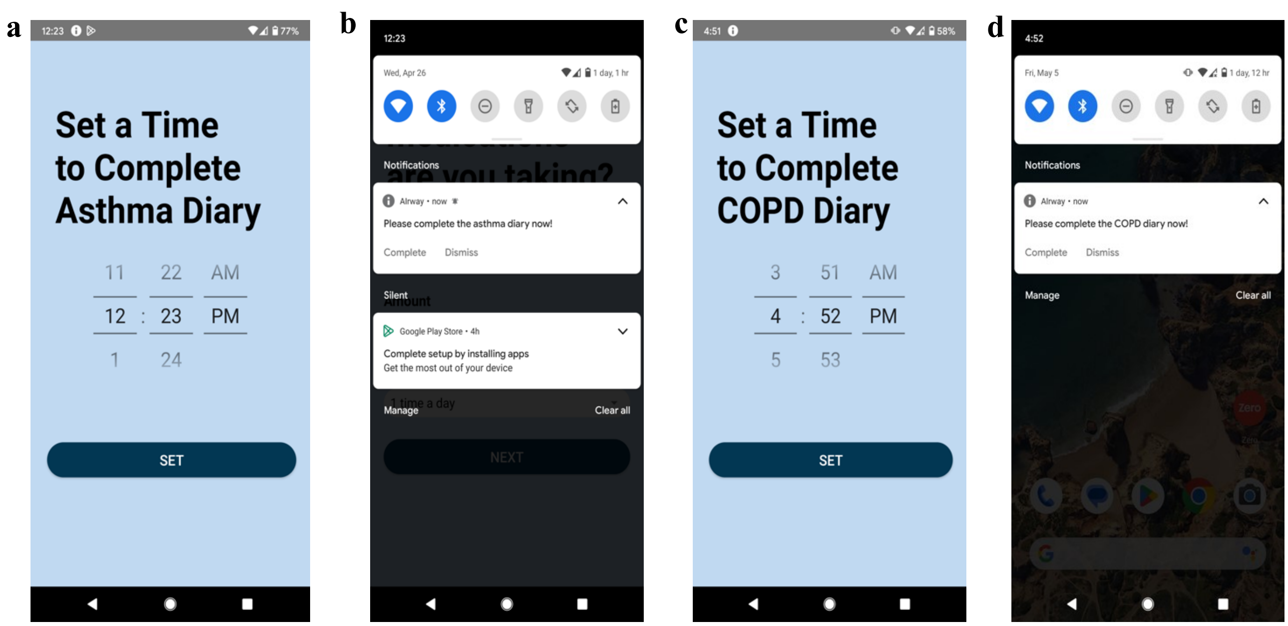


Figure 12. a) Asthma time setting interface b) Asthma diary notification c) COPD time setting interface d) COPD diary notification.

3.2.5 Data Visualization

3.2.5.1 Today Interface: Local Weather Information and Asthma/COPD Control Zone Results

The Today Interface featured both local weather information and the asthma/ COPD control zone of the day. Specifically, an individual's asthma or COPD symptoms can be impacted by air pollution, temperature, and humidity.[102] The World Health Organization (WHO) air quality guidelines recommended four outdoor pollutants namely participle matter (PM), ozone (O3), sulphur dioxide (SO2), and nitrogen dioxide (NO2) as indicators of air quality levels.[103] For example, PM 2.5 (i.e., particle diameter less than 2.5 macros) and PM 10 (i.e., particle diameter less than 10 macros) can deposit throughout airways and cause lung inflammation, which are significant triggers for asthma and COPD patients.[104]

To enhance user awareness and accessibility, the Today interface (**Figure 13a**) provided the local weather information at the users' current location. The interface also included a *Tooltip* feature[105] that displayed a brief message on the definition and the safe level of PM2.5 and PM10 when users clicked on the texts. Users could click dismiss the message by clicking anywhere on the screen, which optimized the screen space.

In addition, healthcare providers often develop a personalized action plan with asthma and COPD patients of how to self-manage and control their symptoms especially when they are severe.[20] The app was designed to emulate a prototype with control zones (Red, Yellow, and Green) and actionable recommendations to support prescribed asthma and COPD self-management. The zone results were generated based on user input from the clinical diaries and clinical standards (see Section 3.3.1.3 and 3.3.1.4 for detail).

3.2.5.2 Report Interface: Clinical Symptom Breakdown

The Report interface (**Figure 13b**) featured a pie chart representing the breakdown of the symptoms. The use of the pie chart design highlighted the percentages of each symptom in different colours so that users could easily view the information at one glance. The generated percentages were meant to emulate the symptom data presentation sent from an external wearable device via Bluetooth Low Energy (Section 3.3.3). This visualization would be useful for users to monitor their symptom status throughout the day.

3.2.5.3 Profile Interface: Account Information Management

The Profile interface (**Figure 13c**) allowed users to view the information they entered during the previous profile setup, including account and emergency contact information, by clicking the corresponding texts or arrow icons. In addition, users could manage their accounts or update the diary schedule at other convenient times as well as log out of their accounts by clicking the "Logout" button.

3.2.5.4 Help Interface: Support, Resources, and Data Privacy

The Help interface (**Figure 13d**) provided users with detailed information about the AIrway app's privacy policy and frequently asked questions (FAQs). The privacy policy was developed in line with the guideline of the Personal Information Protection and Electronic Documents Act (PIPEDA)[106] and Quebec Privacy law[107] to inform users of the type of data that would be collected, and how it would be stored and used (Appendix I). The FAQs provided additional explanations on the development of the asthma and COPD zone calculations, other technical support (e.g., reset password procedure) and the research team's email address for users to reach out if they had any further questions or concerns (Appendix II).

In addition, the Google Firebase Firestore database[54] (Section 3.3.2) used for AIrway app data storage is Health Insurance Portability and Accountability Act (HIPAA)[108] compliant. This means that 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.

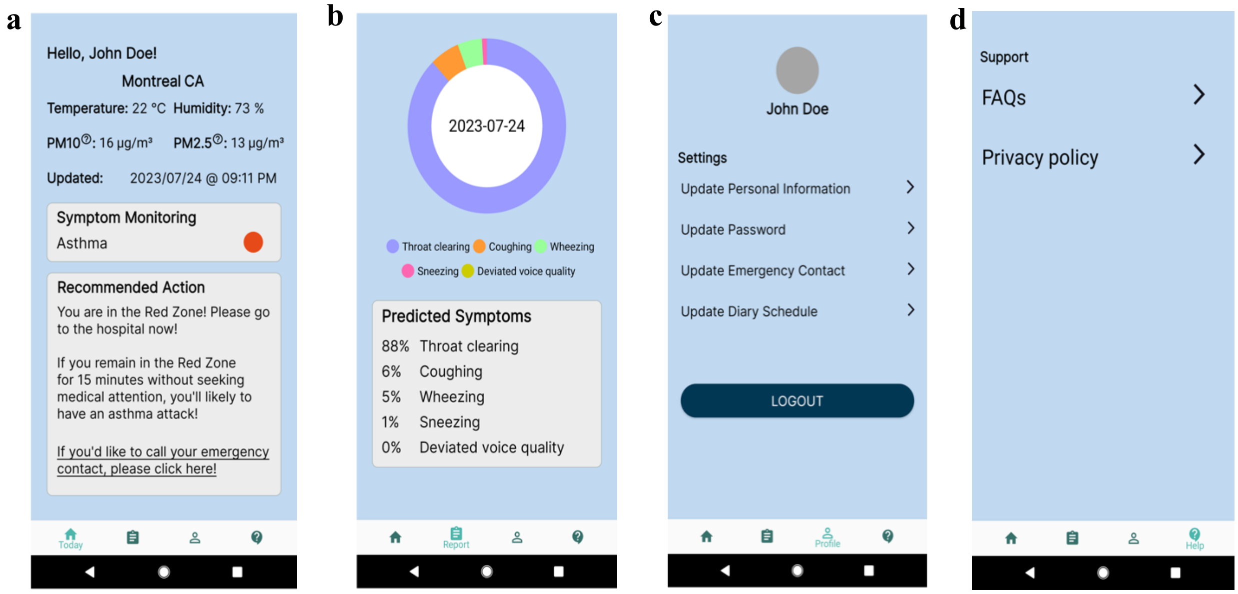


Figure 13. a) Today interface b) Report interface c) Profile interface d) Help interface.

3.3 Backend Development

3.3.1 App Function 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)[84] in Android Studio (Chipmunk 2021.2.1 version)[64] to implement (1) phone call function (2) local weather data retrieval (3) asthma and COPD control zone calculations (4) cloud database storage and retrieval, and (5) Bluetooth Low Energy data transmission.

3.3.1.1 Phone Call Function

The phone call function was developed by storing and retrieving the user's emergency phone call number, which they entered on the Emergency Contact interface. To initiate a phone call from the app, the implementation utilized the $Intent$ class and the $Action\_dial$ method.[109] This call function was put in place for asthma and COPD severe conditions (i.e., Red Zone; See Section 3.3.1.3 and Section 3.3.1.4) and only activated if users clicked the underlined text "*If you'd like to call your emergency contact, please click here!*" on the Today interface. This feature would give users an opportunity to confirm their conditions before making an emergency call. The code snippet for the phone call function is summarized in **Code 2**.

```
red_zone_text.setOnClickListener(new View.OnClickListener() {
    @Override
    public void onClick(View v) {
        Intent intent = new Intent(Intent.ACTION_DIAL, Uri.fromParts("tel", user_phone,
null));
        startActivity(intent);
    }
});
```

Code 2. Phone call function code snippet.

3.3.1.2 Local Weather Data Retrieval

The app retrieved the current local weather information (temperature, humidity, PM2.5, PM10, and the updated timestamp) and displayed them on the Today interface using the OpenWeatherMap API (One Call Version 3.0),[110] an online service that provides the latest forecast data and air pollution information in over 200,000 cities for web and mobile app developers.[111] For example, developers have also utilized the API in their Android apps, such as an app for improving older adults' fitness based on local weather conditions.[112] The code snippet for the weather data retrieval is summarized in **Code 3**.

```
// CALL VALUE IN API for temperature and humidity:
String city_name = jsonObj.getString("name");
String countryname = sys.getString("country");
Long updatedAt = jsonObj.getLong("dt");
String temperature = main.getString("temp");
String humi_dity = main.getString("humidity");
String updatedAtText = new SimpleDateFormat("yyyy/MM/dd @ hh:mm a",
Locale.ENGLISH).format(new Date(updatedAt * 1000));
```

```
// CALL VALUE IN API for pm2.5 and pm10:
   private void FetchAirPollutionIndexFromApi(double latitude, double longitude) {
       AirService.airService.AirInformation(latitude, longitude,
"e52cee364ac0886a6d8878e7fbd3e679")
             .enqueue(new Callback<AirResponse>() {
                 @Override
                 public void onResponse(Call<AirResponse> call, Response<AirResponse>
response) {
                     AirResponse airResponse = response.body();
                     if (airResponse != null) {
                         String getpm_25 =
airResponse.getList().get(0).getComponents().getPm25().toString();
                         String  pm25[]  = getpm_25.split("\\.");
                         pm2_5_text.setText(pm25[0] + " µg/m³");

                         String getpm_10 =
airResponse.getList().get(0).getComponents().getPm10().toString();
                         String  pm10[]  = getpm_10.split("\\.");
                         pm10_text.setText(pm10[0] + " µg/m³");
                     }
                 }
                 @Override
                 public void onFailure(Call<AirResponse> call, Throwable t) {
                     Toast.makeText(getActivity(), "Error" + t.toString(),
Toast.LENGTH_SHORT).show();
                 }
             });
   }
```
Code 3. Local weather data retrieval code snippet.

3.3.1.3 Asthma Control Zone Calculations and Generation of Action Plans

The inputs for the asthma control zone calculations were the user responses from the Asthma Control Questionnaire (ACQ),[94] which contained six items. Each item was measured on a 7-point scale from 0 (no impairment) to 6 (maximum impairment) for symptoms, and the mean score of the six items classified the asthma severity.[94,113] Additionally, the GINA guidelines classified asthma severity into three categories: "*Uncontrolled*," "*Partly Controlled*," and "*Well Controlled*" based on the frequency of the symptoms and exacerbations. The related self-management action items for each category were provided based on the Centers for Disease Control and Prevention (CDC) asthma action plan.[114]

By combining the GINA guidelines and the ACQ mean score, the app implemented a hard-coded classification algorithm using if and $else\ if$ statements to generate the asthma control zone calculations (**Code 4**). The outputs contained two parts: (1) the severity level represented by Red, Yellow, and Green Zones, and (2) the recommended CDC asthma action plan. The details of the asthma control zone calculations corresponding to the self-management actions are summarized in **Table 10**.

```
    if (user_selected_model.equals("Asthma")){
        if (ACQ_average_score > 1.5){
Prediction.setBackground(getResources().getDrawable(R.drawable.prediction_symbol_red));
            action.setText(asthma_managment[0]);
            red_zone_text.setVisibility(View.VISIBLE);
            red_zone_text.setOnClickListener(new View.OnClickListener() {
                @Override
                public void onClick(View v) {
                    Intent intent = new Intent(Intent.ACTION_DIAL, Uri.fromParts("tel",
user_phone, null));
                    startActivity(intent);
                }
            });
        } else if ( ACQ_average_score >= 0.7 && ACQ_average_score <= 1.5)  {

Prediction.setBackground(getResources().getDrawable(R.drawable.prediction_symbol_yello
w));
            action.setText(asthma_managment[1]);
            red_zone_text.setVisibility(View.GONE);
        } else {

Prediction.setBackground(getResources().getDrawable(R.drawable.prediction_symbol_green
));
            action.setText(asthma_managment[2]);
            red_zone_text.setVisibility(View.GONE);
        }
```

Code 4. Asthma zone calculation code snippet.

Table 10. 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	• If the user is still in the Red Zone after 15 minutes and has not reached the doctor, a medical alert will be displayed to suggest there is a possible asthma attack and ask the user to confirm whether an emergency call to be called or go to the hospital now!
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 reminds the user to keep taking Green Zone medicine, suggests taking quick-relief medication, and monitoring the situation for an hour. • If the user does not stay in the Green Zone after an hour, suggest calling a doctor/ nurse before taking oral steroids. • A message about outdoor triggers that are high. If possible, stay inside and close the window.
Green	"Well Controlled" • No (less than twice a week) daytime symptoms OR	• A message to ask the user to indicate the current medication, the amount and frequency.

	• No nocturnal symptoms, exacerbations OR • ACQ score <= 0.75	• A message to encourage the user to keep it up.

3.3.1.4 COPD Control Zone Calculations and Generation of Action Plans

The inputs for COPD control zones the calculations were the user responses from the three validated questionnaires: the breathlessness, cough and sputum scale (BCSS),[99] the COPD Assessment Test (CAT),[96] and the numeric rating scale (NRS).[100] The BCSS questionnaire consisted of three items, each ranging from 0-4 with a total score of 12. A total BCSS score >5 was classified as having a high potential for COPD exacerbations.[99] According to the CAT user guidelines,[115] the CAT questionnaire had eight items, each ranging from 0-5 score with a total score of 40. A total CAT score < 10 was classified as having "*Low Impact*", between 10 and 20 as "*Medium Impact*", and >20 as "*High Impact*" on COPD. The NRS had only one item ranging from 0-10. A total NRS score >5 was classified as having "*Moderate Impact*" and <5 as "*Mild Impact*" on COPD.[100] The related self-management action items for each category were provided based on the Canadian Thoracic Society (CTS) COPD action plan.[116]

Based on the thresholds of the three COPD questionnaires, the app implemented a hard-coded classification algorithm using if and $else\ if$ statements to generate the COPD control zone calculations (**Code 5**). The output consisted of two parts: (1) the severity level represented by Red, Yellow, and Green Zones, and (2) the recommended CTS COPD action plan.[116] The details of the COPD control zone calculations corresponding to the self-management actions are summarized in **Table 11**.

```
else if (user_selected_model.equals("COPD")){
        if (total_bcss > 5 || total_cat >20 || vas >5){
Prediction.setBackground(getResources().getDrawable(R.drawable.prediction_symbol_red));
```

```
            action.setText(copd_managment[0]);
            red_zone_text.setVisibility(View.VISIBLE);
            red_zone_text.setOnClickListener(new View.OnClickListener() {
              @Override
              public void onClick(View v) {
                Intent intent = new Intent(Intent.ACTION_DIAL, Uri.fromParts("tel",
user_phone, null));
                startActivity(intent);
              }
            });
          } else if (total_bcss == 5 || (total_cat <20 && total_cat>10) || vas ==5)  {
Prediction.setBackground(getResources().getDrawable(R.drawable.prediction_symbol_yello
w));
            action.setText(copd_managment[1]);
            red_zone_text.setVisibility(View.GONE);
          } else {
Prediction.setBackground(getResources().getDrawable(R.drawable.prediction_symbol_green
));
            action.setText(copd_managment[2]);
            red_zone_text.setVisibility(View.GONE);
          }
}
```

Code 5. COPD zone calculation code snippet.

Table 11. Summary of COPD zone calculation and action plan in AIrway.

Zone	Thresholds	CTS action plan
Green	• No color change in sputum <u>OR</u> • CAT < 10 <u>OR</u> • BCSS <5 <u>OR</u> • NRS <5	• Keep it up! Use your daily puffers as directed.
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>	• Suggest using prescriptions or COPD flare-ups medications. • If you are on breathing and relaxation methods prescribed by

	• BCSS <5 OR • NRS <5	doctors, use them to pace yourself to relax.
Red	• Symptoms are not better after taking your fare-up medicine for 48 hours OR • Experiencing very short of breath, nervous, confused and/or drowsy, and/ or have a chest pain OR • CAT > 20 OR • BCSS <5 OR • NRS <5	• Please call support contact and/or see your doctor and/or go to the nearest emergency department. • Please call 911!

3.3.2 Cloud Database

Cloud databases are computing servers that can store and send data to be accessed anywhere via the internet without the need for hardware infrastructure.[117] The existing storage of cloud servers can be easily scaled up based on demand which can reduce downtimes and improve performance. Because of the easy access and scalability features, many mHealth apps have integrated cloud databases into their applications for remote and long-term symptom monitoring, such as those for Parkinson's and respiratory diseases.[118,119]

Google Firebase Firestore[54] is an ideal cloud database for the AIrway app for two reasons. First, Firestore can provide real-time updates and easy integration to website, mobile, and Internet of Things (IoT) applications. Other researchers have utilized the Firestore cloud service for their applications, such as an eHealth management system for cardiovascular diseases[120] and a humidity and temperature monitoring system.[121]

Second, traditional databases, such as SQL, require data to be structured in a pre-defined tabular schema with columns and rows. In contrast, Firestore is a NoSQL (not only SQL) cloud database that has no fixed schema and stores data in collections and documents. A collection can contain any number of documents, and a document can contain any number of different types of data, such as strings, numbers, Booleans, arrays or objects, in the form of key-value pairs.[122-124] The AIrway app benefits from this Firestore feature because this feature allows the app to store various types and lengths of user input data (account information, asthma/COPD diary responses, and emergency contact information) in the database.

3.3.2.1 Database Access Feature

To access Firestore from a mobile app, users are required to complete an authentication process with their credentials, such as email and password, phone number, and third-party providers (e.g., Google, Facebook, and Twitter) via the Firebase Authentication Service.[125]

For the AIrway app, the email and password sign-in authentication inputs were programmed in the Register interface (Section 3.2.4.1). Once the user input fields were filled, the $createUserWithEmailAndPassword$ method[125] was used to create an account. If the registration was successful, users were authenticated and a message "*User successfully created!*" would appear. If unsuccessful, a message "*This account already exists. Please register another email!*" would appear preventing users from moving to the next interface. Once users registered, their email and password became a specific sign-in key associated with the user, which could be used to log in and log out of Firestore. The **Code 6** snippet summarizes the implementation.

```
final String email = mEmail.getText().toString().trim();
final String password = mPassword.getText().toString().trim();
fAuth.createUserWithEmailAndPassword(email,password).addOnCompleteListener(new
OnCompleteListener<AuthResult>() {
        @Override
        public void onComplete(@NonNull Task<AuthResult> task) {
```

```
                if(task.isSuccessful()){
                    Toast.makeText(register.this, "User successfully created.",
Toast.LENGTH_SHORT).show();
                }else {
                    email.setError("This account already exists. Please register another
email!")                    }
            }
        });
```
Code 6. The snippet of Firebase authentication code (register.Java).

On the Firebase website, app developers can view the dashboard and manage user authentication based on unique user identifiers (UIDs). The dashboard allows developers to disable or delete accounts, as well as review the account creation and latest time signed-in date (**Figure 14)**. UIDs are automatically generated by the Firebase Authentication Service and assigned to each user associated with their email when the user creates an account. In case of unrecognized emails or UIDs, developers can revoke their access and prevent those users from authenticating to cloud service or accessing the app features.

Developers can also add another security layer by implementing multi-factor authentication (such as an SMS message)[125] during the account login step. Overall, the Firebase Authentication Service allows developers to better secure their apps by managing user accounts and preventing unauthorized access.

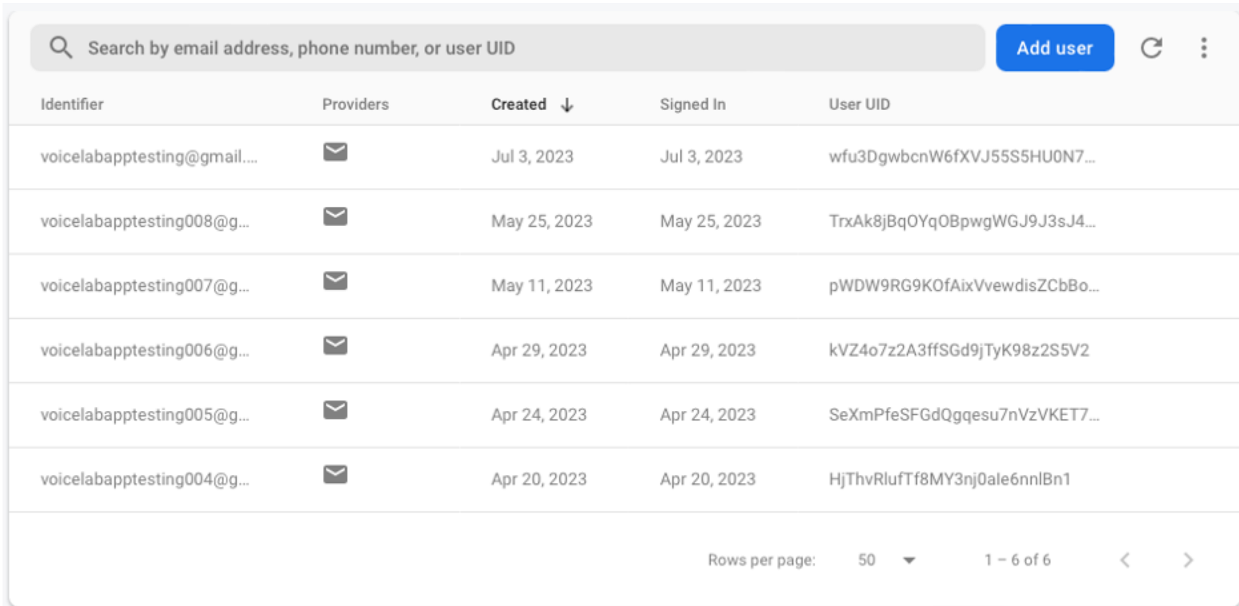


Figure 14. Firebase authentication dashboard.

3.3.2.2 Database Password Reset Feature

As discussed in Section 3.2.4.1, users were provided with the option to rest their passwords by clicking "*Forgot password? Click Here*" in the Login interface. This function utilized the *sendPasswordResetEmail* method[126] provided by the Firebase Authentication Service (**Code 7**). This meant that after users entered a valid email in the Forgot password prompt, the Service would send an email containing a reset link to that email address. Clicking on the reset link allowed users to enter a new password and the Service would update the password for that account. Users could then log in with the new password in the Login interface. The email template for the password reset message is shown in **Figure 15**.

```
   @Override
   public void onClick(DialogInterface dialog, int which) {
      String mail = resetMail.getText().toString();
      fAuth.sendPasswordResetEmail(mail).addOnSuccessListener(new
OnSuccessListener<Void>() {
         @Override
         public void onSuccess(Void aVoid) {
            Toast.makeText(login.this, "Reset link sent to your email.",
Toast.LENGTH_SHORT).show();
         }
```

```
        }).addOnFailureListener(new OnFailureListener() {
            @Override
            public void onFailure(@NonNull Exception e) {
                Toast.makeText(login.this, "Error ! Reset link is not sent" + e.getMessage(),
Toast.LENGTH_SHORT).show();
            }
        });
    }
```

Code 7. The snippet code of password reset code (login.Java).

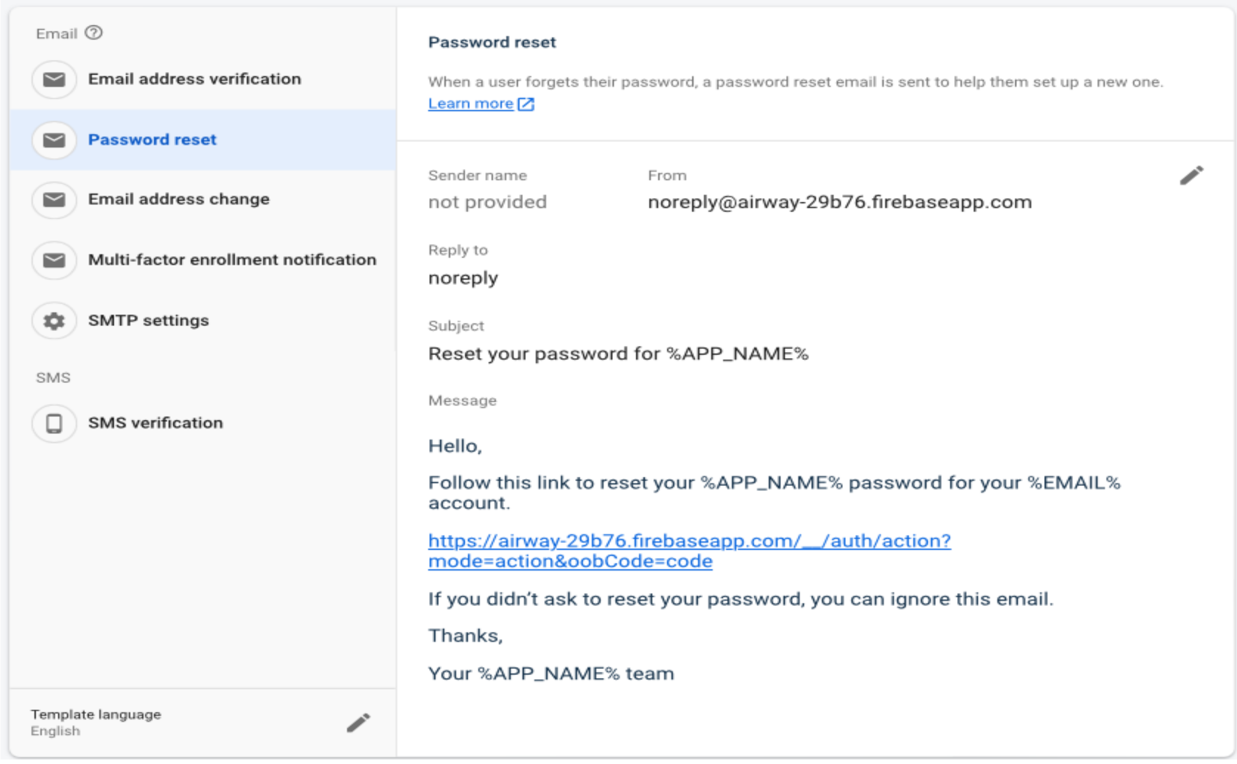


Figure 15. Password reset email template from Firebase Authentication Service.[125]

3.3.2.3 Data Storage

Storing app data in the Firestore database involved three steps. First, the app's access rule for reading and writing data was set to "*True*" to allow authenticated users to make such requests in the app (**Code 8**). Second, on the Android Studio side, the storage path was defined with a collection named "*users*" and a document named after the UID, which was generated during the authentication step. This meant that user data were written under the same collection and each user's specific data was stored in a separate document (**Figure 16**).

```
service cloud.firestore {
  match /databases/{database}/documents {
    match /{document=**} {
      allow read, write: if true;
    }
  }
}
```
Code 8. Firestore read and write rule code.

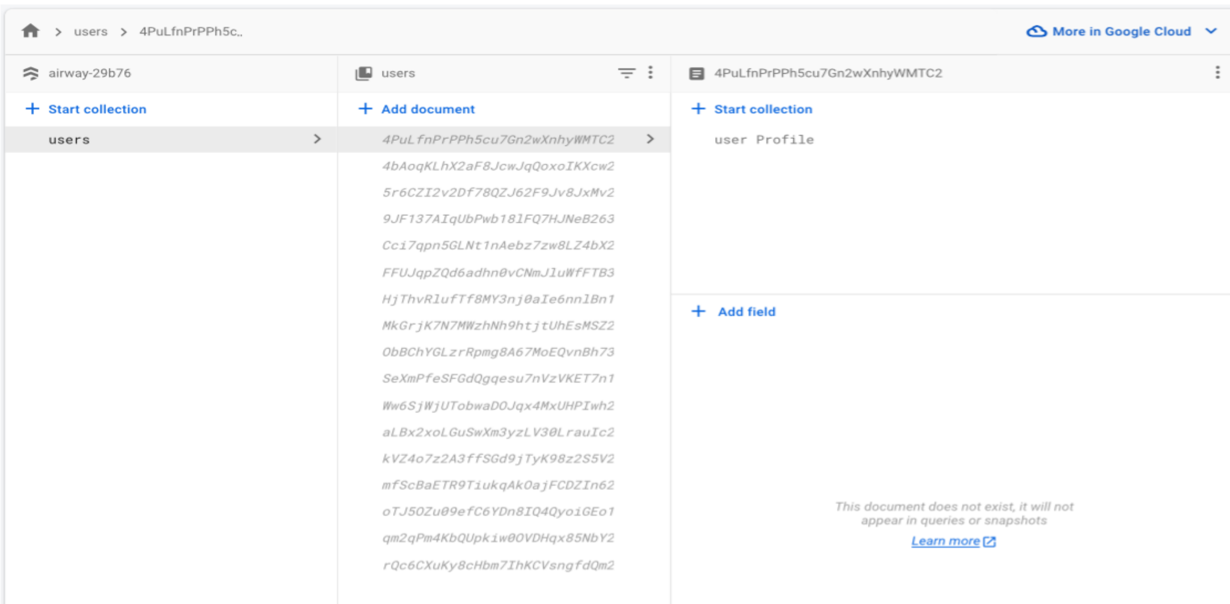


Figure 16. User data path storage with UID.

Third, the $Map < String, Object >$ and $push$ methods[127] were used to add a new data object. For example, one asthma diary question of "*How bad were your asthma symptoms when you woke up in the morning*?" was pushed along with the selected $RadioButton$ response (**Code 9**). The final data was structured under the header "*Asthma Diary Response*" (**Figure 17**).

```
String uid = FirebaseAuth.getInstance().getCurrentUser().getUid();
FirebaseFirestore db = FirebaseFirestore.getInstance();
DocumentReference uidRef = db.collection("users").document(uid).collection("user
Profile").document("Profile");
q1.setOnClickListener(new View.OnClickListener() {
   @Override
   public void onClick(View view) {
      if (q1.isChecked()) {
         Map<String, Object> update = new HashMap<>();
         Map<String, Object> update2 = new HashMap<>();
```

```
            update2.put("How bad were your asthma symptoms when you woke up in the
morning?", answer1);
            update.put("Asthma Diary Response", update2);
            uidRef.set(update, SetOptions.merge()).addOnCompleteListener(new
OnCompleteListener<Void>() {
                @Override
                public void onComplete(@NonNull Task<Void> task) {
                    Toast.makeText(getApplicationContext(), "Response updated ",
Toast.LENGTH_SHORT).show();
                }
            });
        }
    }
});
```
Code 9. Sample code for storing an asthma diary response (asthma.Java).

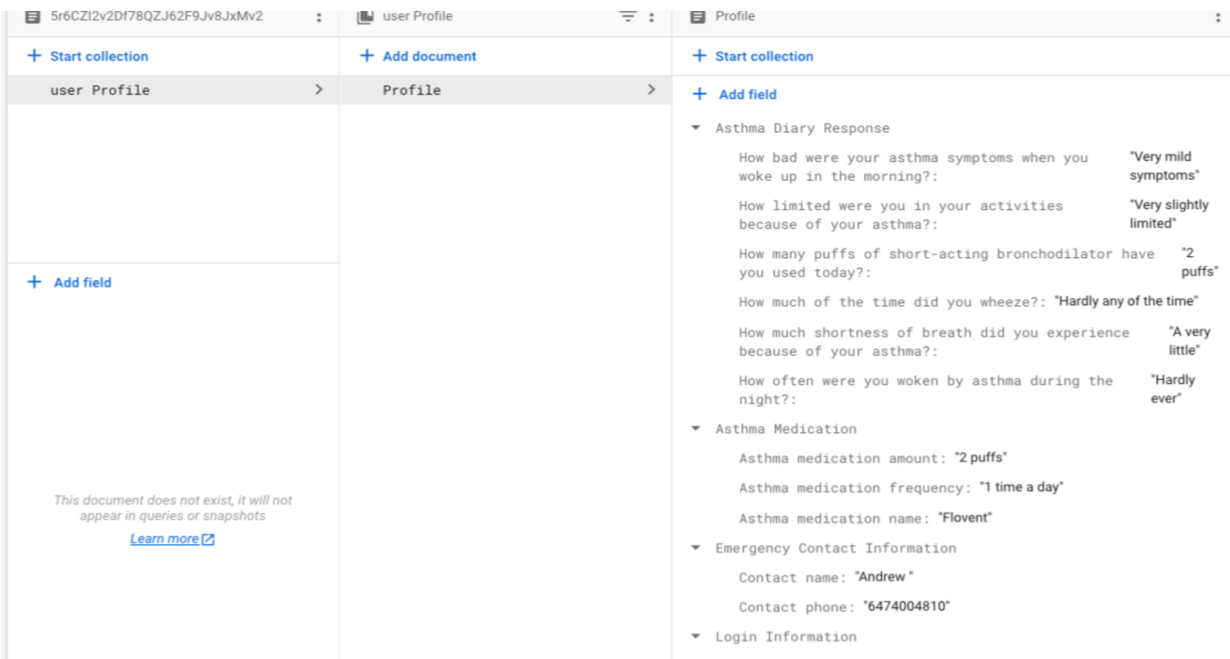


Figure 17. A sample of asthma diary data storage in Firestore.

3.3.2.4 Data Retrieval

The user data could also retrieve back into the app, such as the account and emergency contact data in the Profile interface. In addition to data visualization, data retrieval was a dynamic feature that could increase user retention by allowing users to access personalized data quickly and reminding them of the inputted data before updating them. For instance, if users had a new emergency contact number, this feature ensured users enter the up-to-date information and seek help without barriers in the future.

To achieve this dynamic data retrieval feature, the app first checked if the user document existed. If so, the $getString$ method[128] could obtain the corresponding data on the app. The $setHint$ method[129] would then display the stored data (**Code 10**).

```
if (documentSnapshot.exists()) {
   String user_weight_fb = documentSnapshot.getString("User Information.Weight");
   String user_height_fb = documentSnapshot.getString("User Information.Height");
   String user_gender_fb = documentSnapshot.getString("User Information.Sex");
   String user_date_of_birth_fb = documentSnapshot.getString("User Information.Date of Birth");

   String user_weight_unit = documentSnapshot.getString("User Information.Weight unit");
   String user_height_unit = documentSnapshot.getString("User Information.Height unit");
   mWeight_new.setHint(user_weight_fb);
   mHeight_new.setHint(user_height_fb);
   dateButton.setHint(user_date_of_birth_fb);
}
```

Code 10. Data retrieval implementation sample code (userinformationFragment.Java).

3.3.3 Bluetooth Low Energy Communication

Bluetooth Low Energy (BLE) data transmission is an important function since the app will receive data from an external wearable device. BLE was developed by the Bluetooth Special Interest Group Organization.[130] The BLE communication protocol is ideal for mobile health applications because of its low-energy consumption that can allow small batteries to be embedded in small devices, such as the NSA sensors (Section 1.1).[131]

3.3.3.1 Bluetooth Low Energy Protocol Stack

The BLE protocol stack[132] has two sections, namely controller and host, to enable the data transmission between a device and a mobile app (**Figure 18**). 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.[133]

The host, on the other hand, is at the higher level of the stack that defines the data transmission between devices, including mobile apps.[134] There are two important concepts for BLE establishment in mobile apps: Attribute Protocol (ATT) and Generic Attribute Profile (GATT). The ATT defines the roles of a client-peripheral architecture where the client requests data from the peripheral and then the peripheral sends data to the client.[131] The GATT uses ATT as its transport protocol to exchange data between the clients and servers. In GATT, the data is hierarchically structured in sections called services, which group a collection of user data called characteristics.[135] For instance, to send the device battery information to the app, the developer will set up the GATT that has a battery service. Within the service, it will contain a battery characteristic which represents the power level of the device that can be read by the app.[136]

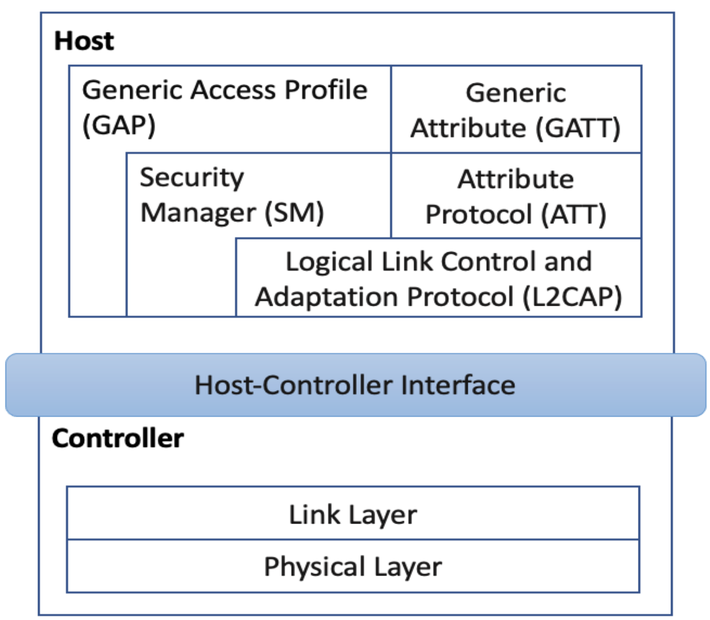


Figure 18. BLE protocol stack (adapted from Texas Instruments Software Developers Guide[132]).

3.3.3.2 Bluetooth Low Energy Scan, Connect, Read Feature

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 and any surrounding BLE devices or sensors act as the peripheral to perform such operations.[137] The AIrway app used the Android BLE API[138] to achieve the BLE scan, connect, and read features (**Code 11**). Overall, this BLE implementation allowed users to perform the following:

- Provide a button to the user to initial scan for surrounding devices using the *BluetoothLeScanner* class.[139]
- Scan and display a list of available results based on the device's name, the Media Access Control (MAC) address (i.e., a hardware identifier that uniquely identifies each device), and the Received Signal Strength Indicator (i.e., a signal strength of the device measured in dBm).
- Connect to the target device using the connectGatt method.[140]
- Read the characteristics (i.e., numerical data) using the *readCharacteristic* method.[141]
- Display a log view to show the read characteristic values in real-time.
- Disconnect the connection.

```
// Scan
mBluetoothAdapter = bluetoothManager.getAdapter();
mLEScanner = mBluetoothAdapter.getBluetoothLeScanner();
scanResultAdapter.notifyDataSetChanged()
bleScanner.startScan(null, scanSettings, scanCallback)
isScanning = true

// Connect
static void connectDevice(int position, Context context){
   ScanActivity obj = (ScanActivity)context;
   obj.mBluetoothGatt =
obj.devices.get(position).connectGatt(context,false,obj.mGattCallback);
}
```

```
// Read
is CharacteristicRead -> with(operation) {
    gatt.findCharacteristic(characteristicUuid)?.let { characteristic ->
        gatt.readCharacteristic(characteristic)
    } ?: this@ConnectionManager.run {
        Timber.e("Cannot find $characteristicUuid to read from")
        signalEndOfOperation()
    }
}
```

Code 11. BLE scan, connect, and read feature code snippet referenced from the Android Bluetooth Low Energy Guide.[137]

After receiving the characteristics, the app efficiently stored the information with timestamps in Firestore. 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 (**Code 12** and **Figure 19**).

```
onCharacteristicChanged = { _, characteristic ->
  log("Value changed on ${characteristic.uuid}:
${characteristic.value.toHexString()}")

  val dateFormatter = SimpleDateFormat("yyyy-MM-dd HH:mm:ss", Locale.getDefault())
  val currentDate = dateFormatter.format(Date())

  val uid = FirebaseAuth.getInstance().currentUser?.uid
  val batterLevel = characteristic.value[0].toInt();
  val db = FirebaseFirestore.getInstance();
  val documentReference =
      db.collection("users").document(uid!!).collection("user Profile")
          .document("Profile")
  documentReference.get()
      .addOnSuccessListener { documentSnapshot ->
          val existingDataList = documentSnapshot.get("BLE data") as? ArrayList<String>
          val dataList = existingDataList ?: ArrayList()
          val combinedValue = "Timestamp: " + currentDate + " Data: " + batterLevel
         dataList.add(combinedValue)
          val dataMap = hashMapOf("BLE data" to dataList)
          documentReference.set(dataMap)
              .addOnSuccessListener {
                  // Data saved successfully dateFormatter.format(Date())
              }
              .addOnFailureListener { e ->
                  // Handle any errors
              }
```

```
        }
        .addOnFailureListener { e ->
            // Handle any errors
        }
}
```
Code 12. BLE data storage code

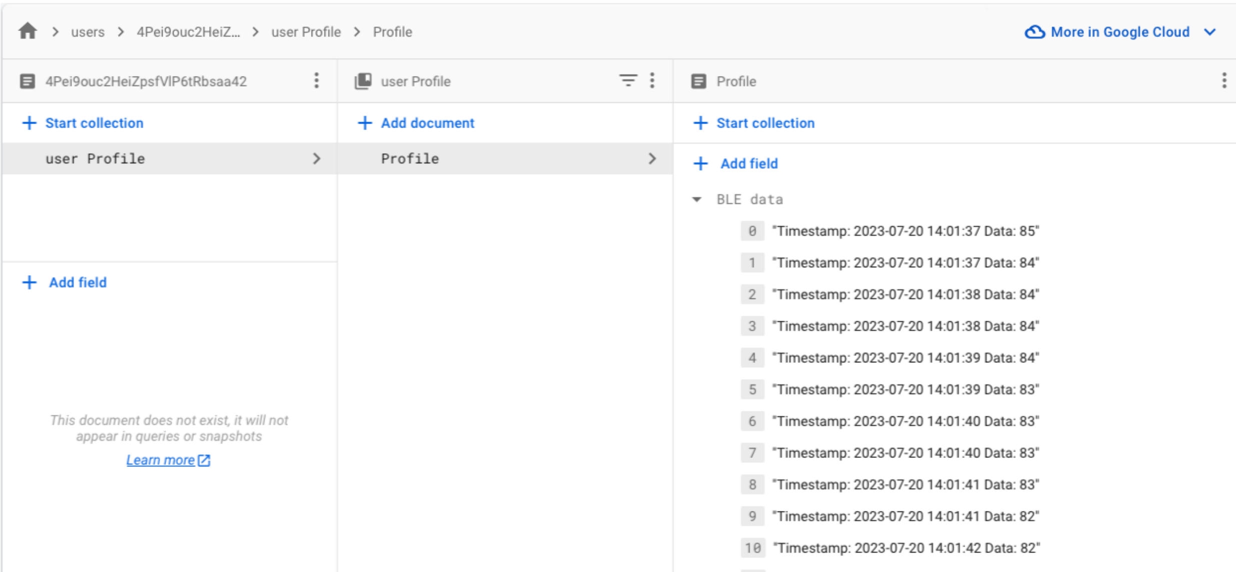


Figure 19. BLE data storage in Firestore

3.3.3.3 Bluetooth Low Energy Experiment Setup

The printed circuit board (PCB) for the final prototype was fabricated based on the nRF5 series microcontroller. Therefore, the nRF52840 Development Board[142] was used to simulate the data transfer, build a ready-to-use BLE protocol, and test the BLE data transmission with the AIrway app. Two services, namely, symptom event classification and the battery level of the DK were programmed by the hardware engineer in the team using C programming language. This simulation advertised these two services to the app with a single characteristic:

- Classification: In considering that an AI algorithm would be deployed to the nRF5 series MCU for symptom classification based on probabilities (e.g., coughing – 87%, wheezing – 3%, and sneezing – 10%) and that will be labelled with an integer number (e.g., 1 = cough, 2 = talking, 3 = breathing), the MCU was set to send the highest probability integer to the app. Simulated random integers from 0 to 5 every 500 milliseconds were programmed to send from the MCU to the app.

- Battery Level: The MCU sent the battery level as an integer, which can range from 0 to 100, to the app. When the device was connected, the device sent the initial value of 100. The value would decrement by 1 every two seconds and reinitiate when it reached 0.

Additional tests were conducted to identify potential factors that could affect the BLE performance. Physical distance (0 – 4 meters), connection time (10 – 40 minutes), and obstacles (microwaves and door) were investigated to evaluate the BLE signal strength, run time, and data transmission. These evaluations were performed with continuous transmission between the board and the app.

3.4 App Usability Evaluation Study

At this initial stage of mobile app development, the primary goal was to collect technical feedback and experience for the AIrway app. As such, app developers (i.e., technical raters) were recruited to test the app's functionality, navigation and design, and provided technical feedback for app improvement. Afterwards, a second phase of the project will be implemented to test the symptom monitoring and disease self-management aspect of the app by recruiting a group of clinical end-users (i.e., individuals with asthma and COPD). The study was approved by the Institute of Review Board of the Faculty of Medicine and Health Sciences at McGill University under the protocol number A12-E39-22B.

3.4.1 Development of App Usability Survey

The usability survey was created and hosted using the McGill IT-managed LimeSurvey platform (version 3).[143] The LimeSurvey contained 51 items including pre-screening (5 items), consent (1 item), and four separate sections (see Appendix III for the complete survey). Sections

A and B measured technical raters' demographics (6 items) and mobile app development experience (5 items). Section C included the User Version of the Mobile Application Rating Scale (uMARS)[144] questionnaire (23 items). Section D included the IQVIA questionnaire[145] (11 items). Technical raters could modify their answers within the same page, but they could not return to previous pages after clicking the "Next" button. While LimeSurvey did not impose a time limitation, it was estimated that completing all the LimeSurvey questions would take approximately 45 minutes.

3.4.1.1 Survey Sections A and B: Demographics and Mobile App Development Experience

Sections A and B included six items for demographics (including occupation) and five items for mobile app development experience (including the app development platform and how many apps they have developed), respectively. These items provided an understanding of the characteristics of the study population and factors that could influence the survey results.[146]

3.4.1.2 Survey Section C: uMARS Questionnaire

Section C was implemented using the uMARS questionnaire, a widely used rating scale for evaluating mHealth apps.[147] uMARS is structured into five sections: engagement, functionality, aesthetics, information quality and subjective quality. The original uMARS questionnaire was modified for clarity and relevance to the specific functions of the AIrway app (**Table 12**). The items were presented using a list style with a single selection in LimeSurvey. Furthermore, an open-text question was added to the end of each section to allow technical raters to provide additional feedback (e.g., "*Do you want to provide more details about app engagement?*").

Table 12. uMARS questionnaire adaptation.

Original uMARS items	**Modified uMARS items**
Section A: Engagement	

Item 1: Entertainment: Is the app fun/entertaining to use? Does it have components that make it more fun than other similar apps?	Item 1: Is the app fun/entertaining to use?
Item 2: Interest: Is the app interesting to use? Does it present its information in an interesting way compared to other similar apps?	Item 2: Is the app interesting to use?
Item 3: Customisation: Does it allow you to customise the settings and preferences that you would like to (e.g., sound, content and notifications)?	Item 3: What do you think of the app content?
	Item 4: Do you want to provide more details about app engagement?
Section B: Functionality	
Item 4: Performance: How accurately/fast do the app features (functions) and components (buttons/menus) work?	Item 5: For the home screen, how accurately is the information displayed (e.g., weather, information, location and time)?
	Item 6: For the home screen, are the buttons and menu fast and responsive?
Item 5: Ease of use: How easy is it to learn how to use the app; how clear are the menu labels, icons and instructions?	Item 7: Is the app easy to use? Are the menus and instructions clear? Are the labels and icons helpful?

Item 6: Navigation: Does moving between screens make sense; Does app have all necessary links between screens?	Item 8: Is login/ register a user account uninterrupted?
Item 7: Gestural design: Do taps, swipes pinches, scrolls make sense? Are they consistent across all components/screens?	Item 9: Are interactions (taps/scrolls) consistent and intuitive across all screens?
	Item 10: Do you want to provide more details about app functionality?
Section C: Aesthetics	
Item 8: Layout: Is arrangement and size of buttons, icons, menus and content on the screen appropriate?	Item 11: Is the arrangement and size of buttons/icons on the screen appropriate?
Item 9: Graphics: How high is the quality/resolution of graphics used for buttons, icons, menus and content?	Item 12: How high is the quality of graphics used for the content?
Item 10: Visual appeal: How good does the app look?	Item 13: How does the app look on the screen?
	Item 14: Do you to provide more details about app aesthetics?
Section D: Information	
Item 11: Quality of information: Is app content correct, well written, and relevant to the goal/topic of the app?	Item 15: Is the weather data relevant to the app?

	Item 16: Is the clinical diary relevant to the app?
Item 12: Visual information: Is visual explanation of concepts – through charts, graphs, images, videos, etc. – clear, logical, correct?	Item 17: Does the help page provide clear, logical, and correct information?
	Item 18: Does the error messaging provide clear, logical, and correct information?
	Item 19: Do you want to provide more details about app information?
Section E: App subjective quality	
Item 13: Would you recommend this app to people who might benefit from it?	Item 20: Do you think the app can be used for self-management purpose (e.g., used by patients daily for monitoring their health conditions)?
Item 14: Would you pay for this app?	Item 21: Would you pay for this app?
Item 15: What is your overall (star) rating of the app?	Item 22: What is your overall star rating of the app?
	Item 23: Would you make changes or add anything to this app? If yes, please describe it below.

3.4.1.3 Survey Section D: IQVIA Questionnaire

The IQVIA questionnaire was also included in the LimeSurvey to assess whether the specific app functions exist. Similar to the uMARS questionnaire, the IQVIA questionnaire is also a validated tool but with specific focuses on evaluating self-management app functions (e.g., alerts, guidance, and communication).[148] Previous studies[148,149] have used both uMARS and IQVIA questionnaires to better assess mHealth apps that targeted self-management purposes. In LimeSurvey, the IQVIA items were presented without modifications as a "*Yes*" or "*No*" response for technical raters to indicate whether the specific app functions were presented (**Table 13**).

Table 13. The IQVIA questionnaire.

Rating description	User response (yes/no)
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	

3.4.2 Study Technical Raters and Recruitment

A convenient sample of app developers (i.e., technical raters) was recruited via an electronic advertisement (Appendix V) with contact information, which was disseminated through

McGill and other Canadian universities' Computer Science student mailing lists and social media. Second, after technical raters indicated their interest in the study, the student investigator sent a pre-screening email to confirm their eligibility and scheduled a 1.5-hour Zoom session with the technical raters who met the criteria.

Inclusion criteria for the app developer group were: (i) over the age of 18; (ii) app developers with at least one year of mobile app development experience, or Computer Science Ph.D. students and post-doctoral fellows who have taken at least one mobile app development course or have conducted a thesis research project on mobile app development; (iii) Android smartphone users who have internet access; and (iv) using English as the main language in daily life. Exclusion criteria were: (v) experiencing severe cognitive and/ or psychiatric conditions that may prevent app developers from completing the study.

Technical raters were compensated for their participation with a $50 CAD Amazon gift card for a total completion time of 1.5 hours. The compensation was deemed appropriate because previous studies[150,151] that recruited developers for mobile app evaluation provided comparable compensation (i.e., between $20-$30 per hour). The 1.5-hour study included the following tasks:

- Pre-screening, demographic, mobile app experience survey completion in LimeSurvey (20 minutes)
- App installation (10 minutes)
- App use and in-app clinical diary completion (35 minutes)
- uMARS and IQVIA survey completion in LimeSurvey (25 minutes)

3.4.3 Study Procedure

During the Zoom session, the student investigator briefly explained the workflow of the study. Afterwards, the technical raters were given a fictitious Gmail address to receive the study materials, including the instruction manual (Appendix IV) and the LimeSurvey (Appendix III).

The manual outlined the study tasks and provided step-by-step instructions to the technical raters so that they could use the app independently. After filling out the sections of pre-screening, consent, demographics and mobile app development experience in LimeSurvey, the student investigator sent an e-mail invitation to the fictitious Gmail from Firebase App Distribution.[152] The technical raters then downloaded and installed the app. Once they finished the required tasks for the app, they were asked to complete the uMARS and IQVIA questionnaires in LimeSurvey.

As recommended by the Checklist for Reporting Results of Internet E-Surveys (CHEERIS)[153] (Appendix VI), an academic guideline for reporting e-surveys, IP addresses and cookies were tracked with the McGill vetted LimeSurvey to help remove duplicated responses. The LimeSurvey data were stored temporarily in a secure Canadian LimeSurvey server for a maximum of 12 months. Once data were exported from LimeSurvey, duplicate responses were discarded, and IP addresses/cookies and all other identifying information were deleted. Technical rater identities were not traceable after this anonymization.

Chapter 4: Results

This section is organized as (1) verification of literacy analysis, (2) BLE experiment result and (3) usability evaluation study result.

4.1 Verification of Literacy Analysis

In addition to the Flesch Reading Ease Score[81] (Section 3.2.2.3), five other readability assessments were performed on the AIrway app's written materials, including the privacy policy, FAQ, asthma action plan, and COPD action plan.

Specifically, the Gunning Fog Index was used to assess the complexity and length of written materials[154] and concluded the materials were suitable for an 8th to 10th grade audience. The Coleman Liau Index assessed the characters of the texts[155] and concluded the materials were suitable for a 7th to 10th grade audience. The Flesch–Kincaid Grade analyzed the words used per sentence of the texts[156] and concluded the materials were appropriate for a 6th to 8th grade audience. The ARI (Automated Readability Index) considered both word and sentence complexity[157] and concluded that the materials were suitable for a 5th to 7th grade audience. The SMOG (Simple Measure of Gobbledygook) index measured the texts based on syllables[158] and concluded that the materials were suitable for a 9th to 10th grade audience.

Literary analysis results are summarized in **Table 14**. Previously, the result of the Flesch Reading Ease Score was close to 60, indicating that general and geriatric populations with a formal education level of grades 9-10 could use the app with ease (Section 3.2.2.3). The five additional assessments aligned with the Flesch Reading Ease Score result, indicating that the readability of the app materials is suitable for a mHealth app targeting geriatric populations with an average reading level of 8-9th grade.

Table 14. Literacy analysis on AIrway app materials.

Readability metrics	Privacy policy	FAQ	Asthma action plan	COPD action plan	Interpretation of the metric[159]
Gunning Fog Index	8.97	9.38	8.44	8.49	8^{th} – 10^{th} grade
Coleman Liau Index	9.18	9.39	7.47	8.35	7^{th} –10^{th} grade
Flesch–Kincaid Grade level	7.57	8.03	7.17	6.80	6^{th} – 8^{th} grade
ARI (Automated Readability Index)	5.94	6.33	4.86	5.38	5^{th} -7^{th} grade
SMOG Index	9.32	9.67	9.06	9.71	9^{th} – 10^{th} grade

4.2 BLE Experiment Result

The BLE experiment was designed to test the BLE data transmission between the AIrway app (client) and the nRF52840 development board (peripheral) (Section 3.3.3.3). First, the app's scan feature accurately detected the development board by its device name, "*NSA BLE,*" with the unique manufacturing MAC address: $D5:D2:5D:62:AF:48$. Second, the signal strength, measured in decibel-milliwatts (dBm) on a logarithmic scale, implies that a closer value to 0 dBm indicates a stronger the signal.[160] For our testing, the development board advertised the highest signal value of -19 dBm among the neighbouring BLE devices (e.g., computers and smartphones), which confirmed its closest proximity to the app. The results are summarized in **Table 15**.

Table 15. 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 the connection was established with the development board, the data read characteristic feature was successfully displayed on the screen and verified with a visual inspection. As mentioned in the experiment setup, simulated battery level data was transmitted using random integers and set to decrement by 1 every two seconds. As expected, the app accurately retrieved real-time data timestamp and the corresponding hexadecimal data value (e.g., 0x0D represents the integer of 13). After two seconds, the value changed from 0x0D (integer 13) to 0x0C (integer 12). This result confirmed the successful integration of the scan, connect, and read characteristic features within the app when interacting with an external device (**Figure 20** and **Figure 21**).

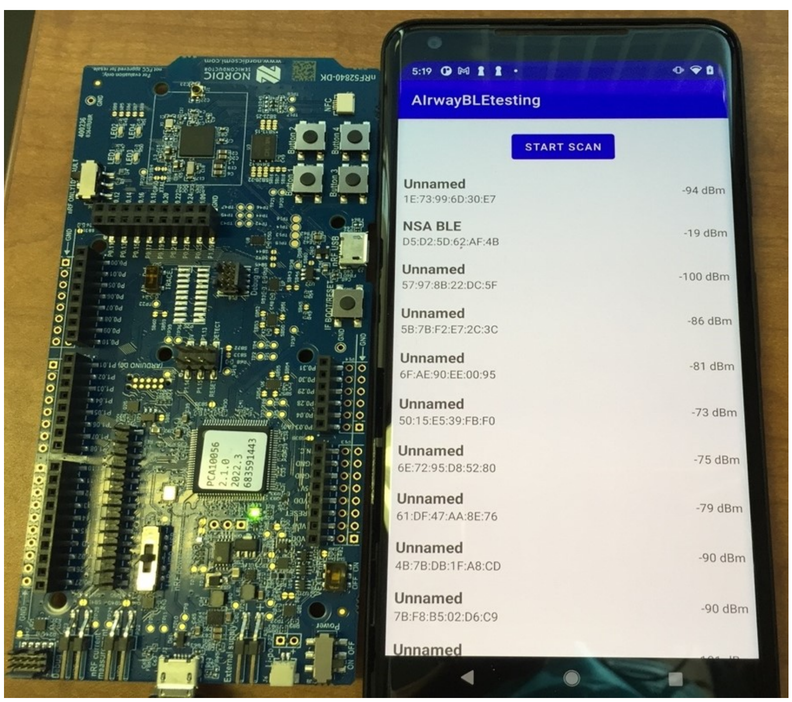


Figure 20. AIrway app performs BLE scan for surrounding devices, including nRF52840 development board (left).

Figure 21. AIrway app performs BLE characteristic read for the classification data from nRF52840 development board (left).

The physical distance, connection time, and obstacles between the development board and the app were found to have an impact on the BLE performance (**Table 16**). The best performance for achieving stable and continuous data streaming was when the two devices were put next to each other without obstacles. However, after a connection exceeded over 10 minutes, some data packet loss was observed. Additionally, occasional disconnection between the devices occurred, mainly observed at further distances apart and likely due to interference from other surrounding BLE devices. In such cases, the app was able to manually reconnect to the board.

Table 16. BLE performance test summary

Task	**Physical Distance**	**BLE 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

4.3 Usability Evaluation Study Result

4.3.1 Technical Rater Profiles

A total of five app developers were recruited as technical raters to rate the AIrway app. Most technical raters were female, visible minorities, resided in Canada, held a bachelor's degree or higher, had a part-time job, and had a mean age of 29.0 years (**Table 17**). Furthermore, most of them were Computer Science Ph.D. students or post-doctoral fellows with 1-2 years of Android mobile app development experience. They had also developed at least 1 app prior to their study participation (**Table 18**).

Table 17. Demographics of technical raters.

Variable	Category	n	%
Gender identity	Male	2	40
	Female	3	60
	Prefer not to answer	0	0
Visible minority status	Yes	4	80
	No	0	0
	I prefer not to answer	1	20
Reside location	United States	0	0
	Canada	5	100
Education level	High school diploma	0	0
	Apprenticeship or trades certificate/diploma	0	0
	College or CEGEP degree/diploma, or university degree lower than bachelor's	1	20
	Bachelor's degree	1	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	0
	Unemployed	0	0
Age		Years	
	Mean	29.0	
	SD	5.61	

Table 18. Mobile app development experience of technical raters.

Variable	Category	n
Primary role	Designing products (e.g., UI designer, interaction designer)	0
	Developing software (e.g., programmer, developer, software engineer)	1

	Testing software (e.g., tester, quality analyst)	0
	Managing software development (e.g., project manager, IT manager)	1
	Computer Science Ph.D. student/ post-doctoral fellow	2
	Other: Software and Hardware Support Analyst	1
Years of experience in mobile development	1-2 years	5
	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 developed	1 app	4
	2-5apps	1
	More than 5 apps	0
Size of the mobile app development team in organization	1-9 employees	3
	10-99 employees	1
	100-999 employees	0
	1,000-9,999 employees	0
	10,000+ employees	0
	Not applicable	1

4.3.2 uMARS Results

The overall mean score for the AIrway app was 3.6 out of 5.0 (SD = 0.2) and indicated above-average quality (>3.0). This score was calculated based on the mean scores of the five sections: 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 section 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. **Table 19** and **Figure 22** summarize the uMARS results.

Table 19. uMARS scores of individual technical raters.

Technical Rater	Engagement	Functionality	Aesthetics	Information quality	Subjective quality	Overall mean
1	4	4.8	3.3	4.3	3.3	**3.9**
2	3.3	3.8	3.3	4.5	3.3	**3.7**
3	3.3	4.2	4.7	4	2.3	**3.7**
4	3.0	4.2	3.0	4.5	2.3	**3.4**
5	3.3	3.8	3.0	4.5	2.7	**3.5**
Mean (SD)	**3.4 (0.4)**	**4.2 (0.4)**	**3.5 (0.6)**	**4.4 (0.2)**	**2.6 (0.3)**	**3.6 (0.2)**

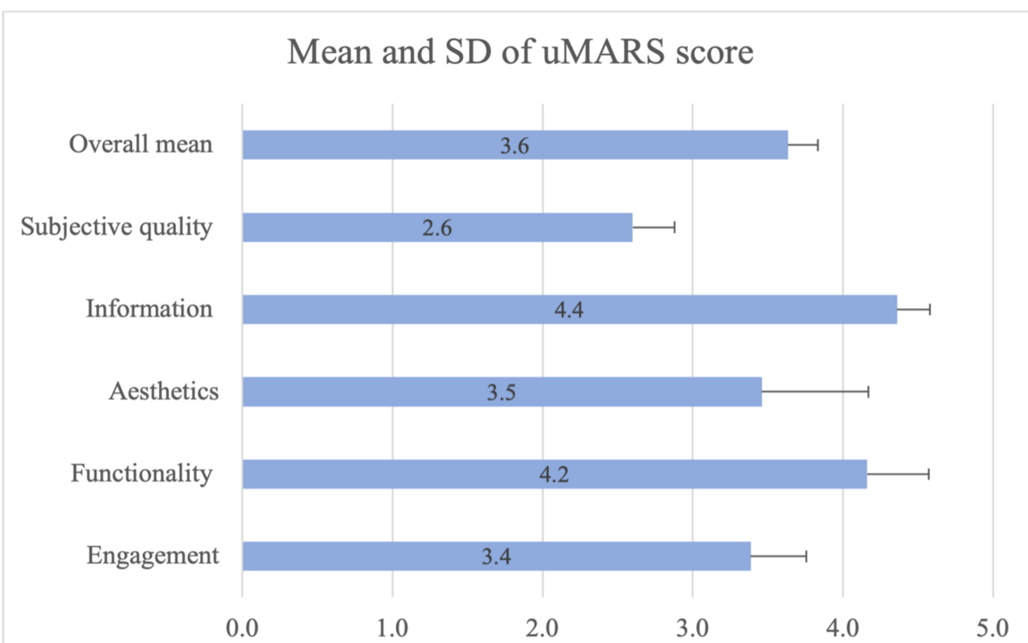


Figure 22. Means and standard deviations (SD) of uMARS scores. N=5

4.3.3 IQVIA Results

The IQVIA functionality score results showed that the total function presented in the AIrway app ranged from 6 – 11 with a median of 8 (SD = 2.1). All technical raters acknowledged the presence of recording, data collection, intervention, display, and alert functions in the app (100% yes). Most of them believed that the user data were able to be evaluated by others (80% yes). More than half of the technical raters expressed that the app had instructing, guiding, and sharing data functions (60% yes). Additionally, only one out of the five technical raters found that the app had 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) (40% yes). **Table 20** and **Figure 23** summarize the IQVIA results.

Table 20. IQVIA results of technical raters.

IQVIA functionality scoring criteria	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Percentage of "Yes"
Inform	Yes	Yes	No	No	No	**40**
Instruct	Yes	Yes	No	No	Yes	**60**
Record	Yes	Yes	Yes	Yes	Yes	**100**
Collect data	Yes	Yes	Yes	Yes	Yes	**100**
Share data	Yes	Yes	No	No	Yes	**60**
Evaluate data	Yes	No	Yes	Yes	Yes	**80**
Intervene	Yes	Yes	Yes	Yes	Yes	**100**
Display	Yes	Yes	Yes	Yes	Yes	**100**
Guide	Yes	No	Yes	No	Yes	**60**
Remind or alert	Yes	Yes	Yes	Yes	Yes	**100**
Communicate	Yes	No	No	No	Yes	**40**
Total functions	**11**	**8**	**7**	**6**	**10**	
Median			**8 (SD = 2.1)**			

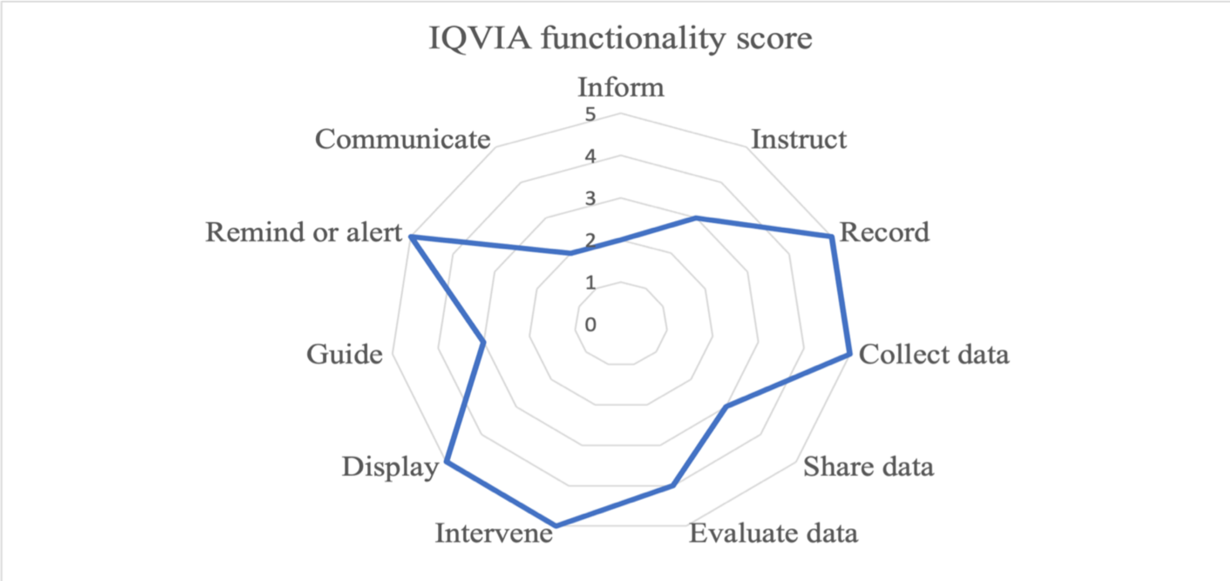


Figure 23. Technical raters' IQVIA functionality score results. N=5

4.3.4 Open-ended Feedback from Technical Raters

Text feedback on the app from technical raters was collected through five open-ended questions regarding the app's engagement, functionality, aesthetics, information quality, and any potential changes to the app. The results are summarized in **Table 21.**

In the engagement section, one technical rater expressed that the "*Forgot Password*? *Click Here*" prompt was not intuitive because the technical rater did not recognize an email was required to reset the password. To improve clarity and consistency, an input box similar to the Login interface's email input field could be used. Another technical rater appreciated the clinical diary reminder for maintaining engagement but suggested that users should be able to navigate to the diary themselves after clicking the "*Complete*" button on the reminder, instead of being automatically directed to the clinical diary. Furthermore, one technical rater did not recognize that the information icons next to PM2.5 and PM10 were clickable for additional explanations, and suggested improving user awareness of the clickable information in the app.

In the functionality section, one technical rater encountered difficulties in the "*Enter a password*" and "*Retype Your Password*" input fields on the Register interface because the entered passwords were not matched. A suggestion was to provide an option to show and hide the passwords on the input fields to allow users to check their entered passwords. Moreover, one recommendation was to include a feature that would allow users to adjust the font size of the information on the screen so that users could view the information at their preferred level.

Regarding aesthetics, two technical raters found that the display of information on the Today interface, such as the texts of temperature, humidity, PM10, and PM2.5, appeared to be crowded. They suggested incorporating more graphical icons to enhance the UI display. Additionally, one suggestion was to utilize more colours for different interfaces and their components, such as incorporating the colours that were used in the Pie chart on the Report Interface.

Regarding information quality, one technical rater suggested increasing the font size of certain texts, such as the "*Support*" title on the Help interface. Another technical rater appreciated the explanation tip for the PM10 and PM2.5 safe levels and recommended a similar explanation tip to be included for temperature and humidity information to help users take necessary precautions.

Overall, the technical raters liked that the AIrway app and its concepts were well-received by the technical raters. One technical rater specifically commented that the app would be likely to be used by patients if the app was recommended by healthcare providers with a free trial strategy. In addition, one suggestion was to incorporate a prompt or an explanation tip to clarify the purpose and frequency of filling out the clinical diary to allow future users better understand its significance.

Table 21. 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 textbook 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.

Chapter 5: Discussion

This section is organized to discuss (1) the uMARS and IQVIA scores in comparison to similar mHealth apps, (2) lessons learnt from the app development as well as (3) study contributions, limitations, and future directions of this research.

5.1 The uMARS and IQVIA Scores in Comparison to Similar mHealth Apps

Our usability study revealed that the AIrway app performed well based on uMARS and IQVIA functionality scores. The overall uMARS mean score was 3.6 out of 5.0, indicating a high level of user satisfaction. In addition, the median IQVIA functionality score was 8 out of 11, suggesting its effectiveness for self-management purposes. The results show that the AIrway app's uMARS and IQVIA scores are on par with commercial mHealth apps in asthma, COPD, flu, COVID, lung and cardiac diseases, and sleep disorders, which typically have a mean MARS score in the range of 3.0-4.2 and a median IQVIA functionality score in the range of 6-10.[148,149,161,162]

These scores aligned with the previously mentioned mobile app design principles (i.e., usefulness, value, findability, credibility, and accessibility) in Section 3.2.1. However, the results also indicated that the app's desirability and usability can be further enhanced. Specifically, from the uMARS result, the AIrway app received the lowest mean score 2.6 out of 5.0 in the subjective quality section. The result indicated that the technical raters believed the app could serve the purpose of self-management, but they were less inclined to pay for its usage or continue using it in the next 12 months. This result is expected since the target functions, such as clinical diaries and reminders, are primarily meant for the end-users (individuals with asthma and COPD). The subjective quality score will be more reflective when testing with clinical populations.

Moreover, two major open-ended comments from the technical raters were that the app should utilize more graphical icons to reduce text for better UI display and improve the input field for the password reset function. These suggestions will be taken into consideration in the next iteration of the app. On the other hand, the IQVIA functionality scores revealed that most technical raters believed that the app lacked sharing and communicating data functions with healthcare providers. In fact, these two functions will be incorporated into the final version of the AIrway app. For instance, by synchronizing with the Firestore cloud services and implementing a user prompt, users can decide whether they want to export the data in an email format or share it with healthcare providers, e.g., respirologists, nurse specialists, family doctors etc.

5.2 Lessons Learnt from the App Development

5.2.1 Effective Strategies for Future App Development

Based on the AIrway app development process, it is critical to have access to a physical Android device throughout the process and conduct rigorous testing with different Android operating systems (OS). Developers should not solely rely on Android emulators for prototyping the app layouts and testing the functions. This is because these emulators have limited capabilities, such as a lack of the ability to initiate and receive phone calls and access Bluetooth hardware. The AIrway app was not fully tested until a real Android phone was available. In hindsight, having early access to a physical device could have accelerated the development and testing process.

All the app functions worked properly on a testing Android phone (Pixel 2L with Android 11 OS). However, prior to the usability study, an unexpected issue occurred in a pilot testing involving different Android phones and systems, namely Samsung S8 with Android 9 OS and Pixel 6 with Android 13 OS. Specifically, the app crashed when navigating to the diary reminder time setting interface on both devices. To debug the cause of the crash, the time setting interface was temporarily excluded from the app and tested again with the users. The crash disappeared, confirming that the $Timepicker$ component was the cause of the problem. Further investigation revealed that the component had a commonly known compatibility issue with some Android OS versions, and it required a proper declaration in the XML file. This crash was resolved before the launch of the usability study.

Overall, this development experience highlighted the limitation of Android emulators and the importance of having access to physical Android devices with various OS versions for rigorous testing. This approach will enable comprehensive app testing and identify any potential bugs and compatibility issues in advance.

5.2.2 The Need of Using Both uMARS and IQVIA Questionnaires

The usability study initially relied on the uMARS questionnaire for the AIrway app evaluation. However, the uMARS questionnaire alone was unable to provide specific self-management evaluation metrics, which were the essential features of the app. To assess the app comprehensively, the IQVIA questionnaire was also included in this study. IQVIA is a pharmaceutical company, formerly known as IMS Health and Quintiles, that developed the IQVIA questionnaire in 2013 to assist mHealth app evaluation because healthcare providers struggled to find the most appropriate app for patients from app stores.[145]

The combination of these questionnaires has been found beneficial in other mHealth app evaluation studies[148,149,162] because they complement each other and provide a multi-dimensional perspective to better understand users' perceptions when they use the app. Specifically, the uMARS scores provided subjective ratings on a scale of 1-5, which allowed the AIrway app to be compared with existing commercial mHealth apps. The additional open-ended questions enabled users to provide any recommendations about the app, such as its layouts, usage of colours or user interaction experience. On the other hand, the IQIVA questionnaire was designed to be a simple tool with a total of 11 "*yes/no*" choices to allow users to determine the presence of specific self-management functions in the app.

Overall, utilizing both uMARS and IQVIA questionnaires is recommended for evaluating similar mHealth apps. This approach ensures a comprehensive assessment of the user experience and provides a full picture of the app's performance.

5.3 Study Contributions, Limitations and Future Research

5.3.1 Study Contributions

This thesis represents an initial technical development of the AIrway app, which aims at supporting a wearable device for COPD and asthma condition monitoring. This thesis provides two significant contributions.

The first contribution lies in the research methods. Most master's level thesis studies[163,164] primarily focused on evaluating existing apps developed by previous researchers. In contrast, this thesis successfully achieved the objectives of designing, developing, and evaluating the AIrway app. In addition, each step of the design and development process in the app followed both recommended technical and clinical guidelines rigorously. For instance, the UX and UI design followed the mobile app design principles and Android development guidelines to enhance the colour contrast of the app's elements, the readability of the written materials, and the layout presentations. Furthermore, asthma and COPD diaries, medication profiles, and action plans were developed based on clinically validated guidelines and standards, such as GINA[74] and GOLD.[29] These steps are essential to meet industrial standards and safeguard the app's credibility, accessibility, and usability.

The second contribution is the technical elements of AIrway. Most respiratory mHealth apps provided only one condition monitoring.[61,165] The AIrway app was developed to support the monitoring of both asthma and COPD conditions paired with a wearable device. This feature not only benefits patients with asthma or COPD, but also benefits patients with asthma-COPD overlap symptoms (i.e., individuals who experience a mix of both symptoms and have more frequent exacerbations, which is more serious than either disease alone and requires close monitoring.)[166] Furthermore, the app was incorporated with a location weather information display, a BLE data transmission feature, and a scalable backend cloud infrastructure for future increased storage. These technical features in the AIrway app are on par with other commercial apps for patients to achieve effective asthma and COPD self-management (**Table 1**).

5.3.2 Study Limitations and Future Directions

The first limitation is that the development process of the AIrway app followed a technical development approach. The Participatory Research Methods guidelines[167] and mHealth development framework[168] propose to actively engage patients in the decision-making process of the app's design and functions for more effective treatment outcomes. However, similar mHealth apps for asthma/ COPD management (e.g., Afflo,[62] Breathe[62] etc.) have already been on the market. For the AIrway app, we included additional features of clinical diaries and local weather information. We decided to first obtain technical evaluations from app developers to ensure that these new features will be error-free and stable. This approach can minimize final users' frustrations, especially since our target group is the geriatric population. Once the app has been refined based on the technical feedback (Section 4.3), a second usability study will be conducted involving patients. This ongoing prototyping development stage provides the flexibility to allow for easy revisions of both the app and the cloud platform and thus patient feedback can be easily adapted. Similar to the first usability, patients will have the opportunity to provide open-ended feedback about the app. The next revision of the app will incorporate valuable inputs from patients before its deployment on app stores.

The second limitation is that the usability study had a relatively low number of technical rater samples (N=5), compared to similar app usability studies which typically have sample sizes ranging from 15 to 40.[151,169,170] This limitation could be attributed to the recruitment channels and requirements. The proposed recruitment channels, such as university CS mailing lists and paid research groups on Facebook, did not effectively target the desired audience. Despite some individuals expressed their interest in the study, they did not meet all the inclusion criteria after receiving the pre-screening email. Given that the recruitment was started in late March 2023, we decided not to pursue changes to the recruitment strategy. This was because submitting an amendment to the McGill Institutional Review Board (IRB) would not align with the timeline for the recruitment and completion of our study. Two future steps can increase the number of technical rater samples. Firstly, the inclusion criteria can be expanded beyond app developers and Computer Science Ph.D. students/post-doctoral fellows who have taken a mobile app development course. For instance, UX and UI designers with at least one year of mobile app design experience can be recruited because they can also provide valuable evaluations based on their front-end design expertise. Secondly, broadening the recruitment channels by reaching out to hackathon events at the local level or across different universities can be an alternative recruitment strategy. For instance, McHacks and HackConcordia in Montreal organize programming challenges for software projects, including mobile app development, and attract skilled developers with frontend and backend expertise. It is important to approach these events well in advance because they typically take place in September and January.

The third limitation is that the AIrway app's native compatibility was restricted to Android devices. As a result, end-users with other mobile app operating systems, such as iOS and Windows Mobile, would not be able to benefit from the AIrway app at this moment. Future work can expand the app's compatibility to other cross-platform mobile app development frameworks, such as Flutter.[171] For instance, the existing Android Java code can be easily converted to Flutter Dart code to achieve a cross-platform version of the AIrway app since both platforms utilized similar packages. This expansion will enable more end-users to use the app regardless of their existing mobile app operating systems, thereby enhancing the app's accessibility and equity.

The fourth limitation is the current BLE performance and data reliability. Our tests indicated occasional disconnection and data packet loss between the development board and the app (Section 4.2). Device connection can be influenced by several factors, such as out-of-range and interference.[172] Since BLE operates in the same 2.4 GHz frequency band as Wi-Fi,[173] radio interference and collisions with surrounding wireless devices, such as smartphones, smartwatches, and computers, may occur. To minimize such interference, the app can implement limited scanning based on the unique manufacturing MAC address of the hardware, i.e., the wearable device. By filtering other surrounding BLE devices, the app can exclusively discover and connect to the target device. Another plausible factor of data packet loss in the app is related to packet size. It is important for the data to fit within a proper Maximum Transmission Unit (MTU), which is the maximum size of a data packet that can be transmitted through the Bluetooth network.[137] The current MTU value in the app is set at the recommended constant of 23,[174] which is capable of transmitting a maximum data size of 20 bytes and hence suitable for the simulated data size of 128 bites/16 bytes in the testing. However, since the maximum data packet size is close to the simulated data size, data packet loss may occur, particularly over a prolonged period.[175] A larger MTU value can potentially reduce data packet loss, but it can also increase latency, i.e., time delay in receiving the data.[137] Therefore, fine-tuning the MTU value to achieve a balance between data reliability and latency may help to optimize the BLE performance.

Further steps can be implemented to enhance the BLE performance and data reliability. First, a customized data transmission schedule can be adopted between the wearable device and the app. During the testing, continuous data streaming was found to cause high battery draining on the phone (about 6% of the phone's battery was consumed within 20 minutes). As a result, the phone will need to be charged throughout the day for continuous transmission, which may not always be feasible and practical for end users. Instead, a customized transmission protocol can be designed to allow the wearable device and the app to send and receive data via BLE periodically or as requested. For example, the data can be scheduled to transmit from the wearable device to the app every half hour. In cases of critical information, such as severe asthma or COPD conditions, the customized transmission protocol will prompt the wearable device to transmit data to the app immediately. This customized approach not only reduces the transmission workload but also ensures effective self-management. In addition, the embedded microSD card in the wearable device can be harnessed for an efficient data storage solution. Raw NSA data can be stored in the card throughout the day, and only critical information (i.e., severe airway conditions) will be sent to the app and stored in the Google Firestore cloud. This implementation ensures no data loss, prevents overwhelming cloud storage, and optimizes power efficiency for both the wearable device and the app.

Chapter 6: Conclusion and Summary

This thesis project represents the first technical milestone in the development of an Android mobile app that supports the data collection and visualization of a neck surface accelerometer (NSA) wearable device for asthma and COPD symptom monitoring.

The frontend development of the app, i.e., user experience and interfaces, followed industrial-level design guidelines to achieve appropriate colour contrast, readability, and layout presentations for the app's target end-users, namely geriatric populations. The backend development included the implementation of symptom diaries, medication profiles, and action plans that were in accordance with current clinical standards for asthma and COPD management. To evaluate the usability of the app, technical raters, namely app developers, were recruited to assess the interfaces and functions of the app through online surveys using uMARS and IQVIA. The results indicated that the app was understandable for both general and geriatric populations. Moreover, the app received satisfactory uMARS and IQVIA scores that were on par with similar mHealth apps in the literature. The feedback from the technical raters highlighted the need to incorporate more graphical icons for better user interface display and to improve the input field of the password reset function.

Future steps will incorporate the feedback provided by the technical raters to enhance the app's user interfaces and functions as well as expand the app's compatibility to other platforms beyond Android.

Appendices

Appendix I: 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
- Phone number
- Emergency contact
- 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
- PM 2.5
- PM 10
- Latest updated timestamp

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.

<u>How do we use the information?</u>
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

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

<u>Where do we store the information?</u>
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.

<u>How long do we store the information?</u>
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 II: Frequently Asked Questions for the App

1. **How may the AIrway app benefit me?**
   - The AIrway app aims to put you in control of your asthma or COPD-related symptoms and allows you to actively be aware of the triggers that can worsen your conditions. The goal is to help you learn how to make positive choices and better manage your respiratory health.

   - With AIrway, you will be able to:
     - View the weather conditions based on your location
     - View the current and past prediction results to manage your conditions
     - Set and receive reminders about your clinical diary and medications
     - Receive the recommended actions based on your conditions
2. **How did you get my asthma prediction?**
   - The asthma diary was developed based on the Asthma Control Questionnaire (ACQ). Based on your response, we use the results of ACQ to predict your zone of control for your asthma.

     For more information, please go to: https://www.thoracic.org/members/assemblies/assemblies/srn/questionaires/acq.php
3. **How did you get my COPD prediction?**
   - The COPD diary was developed based on the breathlessness, cough and sputum scale (BCSS),19 the numeric rating scale (NRS), and the COPD Assessment Test (CAT). Based on your response, we use the results of BCSS, NRS, and CAT to predict your zone of control for your COPD.

     For more information, please go to: https://www.astrazeneca.com/content/dam/az/orphan-page-files/Patient%20Reported%20Outcomes/BCSS_eng-AU.PDF

     https://pubmed.ncbi.nlm.nih.gov/9579246/

     https://www.catestonline.org/patient-site-test-page-english.html

4. **What is an action plan?**
   - If you have asthma or COPD, you should have been given an action plan by your healthcare provider to manage your related symptoms. If you don't have an action plan, you can visit your doctor and ask for one.

     For asthma, we adopt the key parts of the CDC Asthma Action Plan that has three zones (Green, Yellow, and Red) with a set of instructions to recommend what you should do to manage your asthma when you are in each zone. For more information, please go to: https://www.cdc.gov/asthma/action-plan/documents/asthma-action-plan-508.pdf

5. **What does the prediction mean?**
    - The prediction represents the likelihood of your asthma or COPD severity based on clinical guidelines. It is not intended to provide medical information, diagnose, treat, or cure any disease. If you experience a medical emergency, stop using the app and consult your doctor immediately.

6. **What should I do if I forget my password?**
    - If you forget your password, you can reset it by first logging out of this app. This will bring you back to the user login page. You can select the "Forget password?" option. Please enter your email. You will receive a link to reset your password.

7. **Can I still receive reminders if my screen is locked?**
    - Yes. To receive reminders from the AIrway app even if your screen is locked, you need to ensure that your phone is not in "Do Not Disturb" mode. Furthermore, under Setting > Sound & Notifications > "When device is locked", you should ensure the notification preference "show all notification content" is selected.

8. **Who made the AIrway app?**
    - The AIrway app was developed by the Voice and Upper Airway Research Lab at McGill University in Canada in collaboration with researchers at the University of Erlangen-Nuremberg in Germany.

      Our group consists of researchers, speech-language pathologists, and engineers. We are improving personalized medicine in voice and upper airway dysfunctions with advanced technology. Feel free to check out our website for other projects: https://voice.lab.mcgill.ca/

      We thank our sponsors who made this project possible. The project is funded by Fonds de recherche du Québec (FRQ) and the Centre for Research on Brain, Language and Music (CRBLM).

9. **My question is not listed here**
    - Don't worry! Please send us an email to: voicelab.mcgill@gmail.com with your questions and our team will get back to you very soon!

Appendix III: Final LimeSurvey Questions for the Study

Below is the content in the final survey for the app developer. Text in italics is for the student investigator's information only when developing the survey, and was not visible to participants.

WELCOME MESSAGE

Welcome to our study about the user experience with an Android mobile app. We will start with a few simple questions to ensure that you fit our study criteria. After that, there will be a consent form and mobile app experience questionnaires for you to complete. You will then be presented with further study participation instructions, and finally you will complete the User Version of the Mobile Application Rating Scale (uMARS) questionnaire.

You can save your progress and return at any time, but you cannot go back to previous questions after you have moved to the next page. Click next to continue.

PARTICIPANT SCREENING

X1 **Are you over the age of 18?**

a. Yes
b. No

X2 **What percentage of your daily language use is in English?**

a. 100%
b. 80-99%
c. 60-79%
d. Less than 60%

X3 **Are you an app developer who has at least one year of mobile app development experience?**

a. Yes
b. No

X4 **Are you a Computer Science Ph.D. student/ post-doctoral fellow who has taken at least one mobile app development course or has conducted a thesis research project on mobile app development?**

a. Yes
b. No

X5 **Do you have an Android phone and internet access?**

a. Yes
b. No

Participants who answer yes in X1, X3, X5, a-c in X2, and yes in either X3 or X4 are able to continue to the consent section. Otherwise, they will see the following message:

"Thank you for responding to our survey. Unfortunately, you don't quite fit what we're trying to study."

CONSENT SECTION (a complete consent form will be provided to participants in advance of data collection.)

Do you want to participate in this study to evaluate a mobile app?

a. Yes
b. No

Participants who answered "yes" will become a part of the app developer group for this study. Participants who do not consent to participate will see the following message:

Thanks for considering our study, we're sorry to see you go! If you have concerns about the study, you can contact us at the following locations:

Nicole Li-Jessen, principal investigator: nicole.li@mcgill.ca or 514-398-5933

Lisa Martignetti, study coordinator: lisa.martignetti@mail.mcgill.ca or 514-398-6222

Andrew Chao, student investigator: usan.chao@mail.mcgill.ca

If you have any ethical concerns or complaints about your participation in this study, and want to speak with someone who is not on the research team, please contact Ms. Ilde Lepore, Ethics Officer of the McGill Institutional Review Board, at 514-398-8302 or ilde.lepore@mcgill.ca.

Participants who do consent to participate are able to proceed to the rest of the study.

* *Disclaimer*: The goal of the study is to test a mobile app that is under the initial developmental phase only. The app is not intended to provide medical information, diagnose, treat, or cure any disease. If you experience a medical emergency, stop using the app and consult your doctor immediately.

A – Demographics

A-1 **What gender do you identify as?**

a. Male
b. Female
c. I prefer not to answer
d. Other: ________

A-2 **Are you a member of a visible minority?**

a. Yes
b. No
c. I prefer not to answer

A-3 **What is your age? (Years)**

____

A-4 **In which country and city do you currently reside?**

a. United States
b. Canada
c. Other: ________

A-5 **What is the highest level of education that you have completed?**

a. High school diploma
b. Apprenticeship or trades certificate/diploma
c. College or CEGEP degree/diploma, or university degree lower than bachelor's
d. Bachelor's degree
e. Graduate degree (master's or doctorate)
f. None of the above

A-6 **What is your job status?**

a. Full-time (>30 hours per week) employed
b. Part-time (<30 hours per week) employed
c. Self-employed
d. Unemployed

B - Mobile app development experience

B-1 **Please select the statement that best describes your primary role at your current or most recent job.**

a. Designing products (e.g., UI designer, interaction designer)
b. Developing software (e.g., programmer, developer, software engineer)
c. Testing software (e.g., tester, quality analyst)
d. Managing software development (e.g., project manager, IT manager)
e. Computer Science Ph.D. student/ post-doctoral fellow
f. Other: __________

B-2 **How many years of experience do you have in mobile app development?**

a. 2-3 years
b. 3-4 years
c. More than 5 years

B-3 **Which mobile app development platforms do you have expertise in? (Please click all that apply)**

a. iOS
b. Android
c. Windows
d. BlackBerry
e. Other(s): __________

B-4 **How many mobile apps have you developed?**

a. 1 app
b. 2-5 apps
c. More than 5 apps

B-5 **What is the size of the mobile app development team in your organization?**

a. 1-9 employees
b. 10-99 employees
c. 100-999 employees
d. 1,000-9,999 employees
e. 10,000+ employees
f. Not applicable

C – 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.

____

D - 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 IV: Study Instruction Manual

<u>Mobile app user experience evaluation instruction manual</u>

Welcome to this research study of McGill Voice and Upper Airway (VUA) Research Lab! You will download and use the app and fill out the LimeSurvey questionnaires. You should receive a link to open the LimeSurvey and a Gmail address and password for use in the study. The student investigator will guide you during the Zoom call.

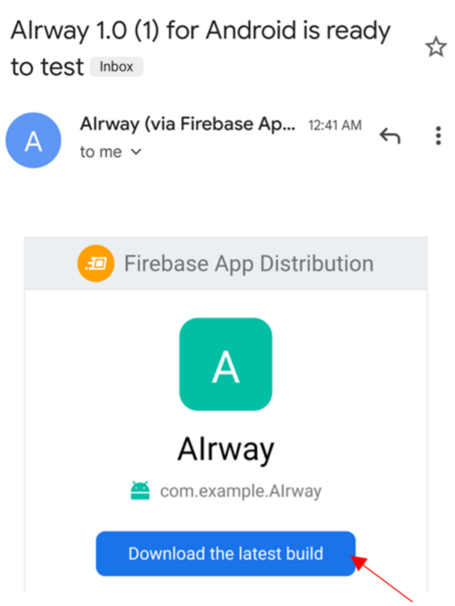
Part 1: Eligibility check

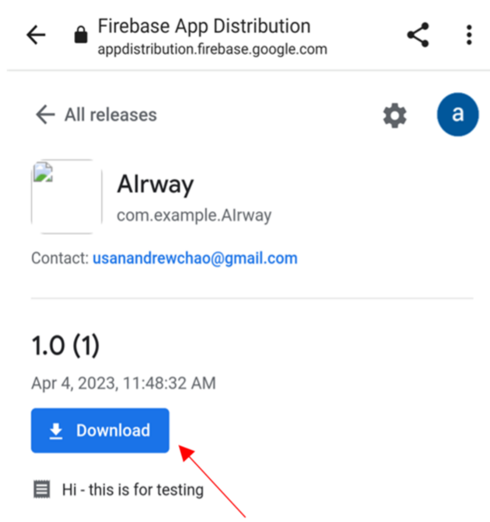
1. Complete the pre-screening questions **with your information** (Note: if you see the message: "*Thank you for responding to our survey. Unfortunately, you don't quite fit what we're trying to study*.", you are not eligible for the study. The study will be terminated).
2. Complete the demographic questions **with your information.**
3. Complete the mobile app experience questions **with your information.**

*****Please stop here once you complete the mobile app experience questions and let the student investigator know and wait for further instructions *****

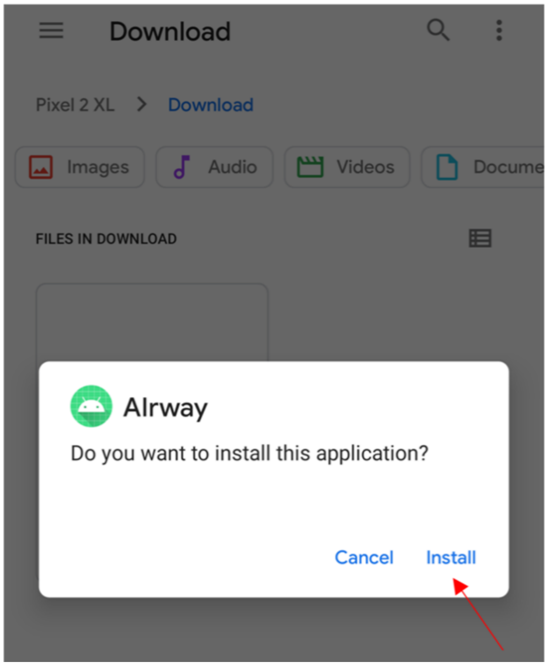
Part 2: Download the app

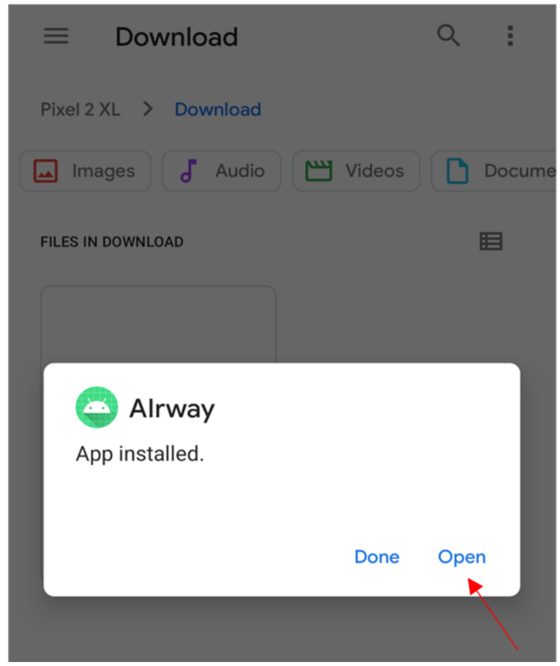
4. Login to **the given Gmail account** on your phone. You should receive an email invite to download the app. Click "Download the latest build" and "Download" following the screenshots shown below.





5. Click “Install” and “Open” the app when you see the notifications. The app will be installed on your Android phone and it’s now ready for testing!





*Note: An alert appears if you are running an Android app that hasn't been given permission to outside of Google Play. To grant permission:

- Android version 8 or later: In the Settings app, tap Allow from this source.
- Android version 7 or earlier: In the Settings app, tap Security and select Unknown sources. When the prompt appears, tap OK > Trust.

Part 3: Use and evaluate the app

Once you download and open the app, please follow the steps below to complete the study.

In App

6. Click “New User? Register Here” to register an account:
    a. Enter Full Name **with fictitious information**
    b. Enter Email **using the given Gmail address**
    c. Enter Password **with fictitious information**
    d. Select either Asthma or COPD condition
7. Enable the location permission by choosing “Only this time”.
8. Fill out the “Tell Us More About You” page for Sex, Date of Birth, Weight and Height **with fictitious information.**

9. Fill out the “Emergency Contact” page with the following information:
    e. Contact name: **Andrew**
    f. Contact phone: **438-867-9752**
10. Select **a fictitious choice** from the medication, amount, and frequency drop-down menu.
11. Scroll the timer to set **5 minutes** after the current time for the diary reminder.
12. Response to the corresponding diary by **selecting a fictitious choice.**
13. View and check the weather accuracy and information displayed on the “Today” page.
    g. Click the PM10 and PM 2.5 labels to view the information
14. Click the “Report” icon at the bottom screen (next to “Today”) to view the information.
15. Click the “Profile” icon (next to “Report”) to test all features, including “Update Personal Information” and “Update Password” **using fictitious information.**
16. Click the “Help” icon (next to “Profile”) to view the FAQ and privacy policy content.
17. Click the “Profile” icon and click the logout button.
18. Login with **the new password you updated**.
19. After 5 minutes, you should receive the diary reminder in your notification center appeared on your phone. Click “Complete” and it will you bring back to the diary. **This time, please select the last choice for all the diary questions.**
20. On the “Today” page, click the underlined text “Call Your Emergency Contact” under recommended action. This will initiate a call to the number you entered (our lab phone). Please wait for **about 10 seconds** and we then will hang up the call.
21. Logout again on the “Profile” page.
22. Click “Forgot Password? Click Here” on the “Login” page and **enter your given Gmail** in the password reset popup.
23. Open **the given Gmail account**, you should receive a reset link to reset your password. Click the link and reset the password. **Login again with the new password you reset.**
24. Logout and you have now completed using the app.

In LimeSurvey

25. Complete the uMARS questionnaire.
26. Complete the IQVIA questionnaire.

You have now completed the study! Please delete the app on your phone and show your phone screen to the student investigator via Zoom to confirm its deletion. Please inform the

student investigator of your email address to receive the $50 Amazon gift card compensation. We will contact you within two weeks via the email address voicelab.mcgill@gmail.com for gift card distribution. Thank you for your participation!

Appendix V: Electronic Advertisement for the Study

Mobile App Usability Study

McGill UNIVERSITY

SCSD
School of Communication Sciences and Disorders

In the study, the participants will:

- Download and use an Android app (45 minutes)
- Complete a survey about demographics, mobile app development experience, and app usability (45 minutes)
- Estimated total time commitment is 1.5 hours

To participate, you must:

- Be aged over 18 years old
- Use English as your main language in daily life
- Have an Android smartphone and internet access
- Have at least one year mobile app development experience OR
- Be a Computer Science Ph.D. student/ post-doctoral fellow who has taken at least one mobile app development course or conducted a thesis research project on mobile app development

Participants will receive a $50 CAD Amazon gift card for their participation.

Please contact the student investigator to verify your eligibility for the study. For more information, send an email with APP USABILITY STUDY in the subject field to: usan.chao@mail.mcgill.ca (Student Investigator: Andrew Chao). The study was approved by the Institutional Review Board at McGill University (A12-E39-22B).

Appendix VI: Checklist for Reporting Results of Internet E-Surveys (CHERRIES)

The CHERRIES guidance is referenced and shown below[153]. The page number indicates the adoption of the guidance components for the usability study.

Checklist Item	Explanation	Page Number/ Comments
Describe survey	Describe target population, sample frame. Is the sample a convenience sample? (In "open" surveys this is most likely.)	61-68
IRB approval	Mention whether the study has been approved by an IRB.	61
Informed consent	Describe the informed consent process. Where were the participants told the length of time of the survey, which data were stored and where and for how long, who the investigator was, and the purpose of the study?	68
Data protection	If any personal information was collected or stored, describe what mechanisms were used to protect unauthorized access.	Not applicable, we did not collect identifiable personal information
Development and testing	State how the survey was developed, including whether the usability and technical functionality of the electronic questionnaire had been tested before fielding the questionnaire.	61-66
Open survey versus closed survey	An "open survey" is a survey open for each visitor of a site, while a closed survey is only open to a sample which the investigator knows (password-protected survey).	"Closed"
Contact mode	Indicate whether or not the initial contact with the potential participants was made on the Internet. (Investigators may also send out questionnaires by mail and allow for Web-based data entry.)	676
Advertising the survey	How/where was the survey announced or advertised? Some examples are offline media (newspapers), or online (mailing lists – If yes, which ones?) or banner ads (Where were these banner ads posted and what did they look	67

	like?). It is important to know the wording of the announcement as it will heavily influence who chooses to participate. Ideally the survey announcement should be published as an appendix.	
Web/E-mail	State the type of e-survey (eg, one posted on a Web site, or one sent out through e-mail). If it is an e-mail survey, were the responses entered manually into a database, or was there an automatic method for capturing responses?	Send through email
Context	Describe the Web site (for mailing list/newsgroup) in which the survey was posted. What is the Web site about, who is visiting it, what are visitors normally looking for? Discuss to what degree the content of the Web site could pre-select the sample or influence the results. For example, a survey about vaccination on a anti-immunization Web site will have different results from a Web survey conducted on a government Web site	67
Mandatory/voluntary	Was it a mandatory survey to be filled in by every visitor who wanted to enter the Web site, or was it a voluntary survey?	Voluntary survey
Incentives	Were any incentives offered (eg, monetary, prizes, or non-monetary incentives such as an offer to provide the survey results)?	67
Time/Date	In what timeframe were the data collected?	Not applicable
Randomization of items or questionnaires	To prevent biases items can be randomized or alternated.	Not applicable
Adaptive questioning	Use adaptive questioning (certain items, or only conditionally displayed based on responses to other items) to reduce number and complexity of the questions.	98-107
Number of Items	What was the number of questionnaire items per page? The number of items is an important factor for the completion rate.	61

Number of screens (pages)	Over how many pages was the questionnaire distributed? The number of items is an important factor for the completion rate.	61
Completeness check	It is technically possible to do consistency or completeness checks before the questionnaire is submitted. Was this done, and if "yes", how (usually JAVAScript)? An alternative is to check for completeness after the questionnaire has been submitted (and highlight mandatory items). If this has been done, it should be reported. All items should provide a non-response option such as "not applicable" or "rather not say", and selection of one response option should be enforced.	Yes; see 98-107
Review step	State whether respondents were able to review and change their answers (eg, through a Back button or a Review step which displays a summary of the responses and asks the respondents if they are correct).	61
Cookies used	Indicate whether cookies were used to assign a unique user identifier to each client computer. If so, mention the page on which the cookie was set and read, and how long the cookie was valid. Were duplicate entries avoided by preventing users access to the survey twice; or were duplicate database entries having the same user ID eliminated before analysis? In the latter case, which entries were kept for analysis (e.g., the first entry or the most recent)?	68
IP check	Indicate whether the IP address of the client computer was used to identify potential duplicate entries from the same user. If so, mention the period of time for which no two entries from the same IP address were allowed (e.g., 24 hours). Were duplicate entries avoided by preventing users with the same IP address access to the survey twice; or were duplicate database entries having	68

	the same IP address within a given period of time eliminated before analysis? If the latter, which entries were kept for analysis (e.g., the first entry or the most recent)?	
Log file analysis	Indicate whether other techniques to analyze the log file for identification of multiple entries were used. If so, please describe.	68
Registration	In “closed” (non-open) surveys, users need to login first and it is easier to prevent duplicate entries from the same user. Describe how this was done. For example, was the survey never displayed a second time once the user had filled it in, or was the username stored together with the survey results and later eliminated? If the latter, which entries were kept for analysis (e.g., the first entry or the most recent)?	IP address was collected and each entry only showed once after user moved to the next page.
Handling of incomplete questionnaires	Were only completed questionnaires analyzed? Were questionnaires which terminated early (where, for example, users did not go through all questionnaire pages) also analyzed?	Not Applicable
Questionnaires submitted with an atypical timestamp	Some investigators may measure the time people needed to fill in a questionnaire and exclude questionnaires that were submitted too soon. Specify the timeframe that was used as a cut-off point, and describe how this point was determined.	Not Applicable
Statistical correction	Indicate whether any methods such as weighting of items or propensity scores have been used to adjust for the non-representative sample; if so, please describe the methods.	Not Applicable

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