

Marquette University

e-Publications@Marquette

---

Master's Theses (2009 -)

Dissertations, Theses, and Professional  
Projects

---

## Improving Benign Paroxysmal Positional Vertigo Diagnosis

Sida Zhang  
*Marquette University*

Follow this and additional works at: [https://epublications.marquette.edu/theses\\_open](https://epublications.marquette.edu/theses_open)



Part of the [Engineering Commons](#)

---

### Recommended Citation

Zhang, Sida, "Improving Benign Paroxysmal Positional Vertigo Diagnosis" (2023). *Master's Theses (2009 -)*. 777.

[https://epublications.marquette.edu/theses\\_open/777](https://epublications.marquette.edu/theses_open/777)

IMPROVING BENIGN PAROXYSMAL POSITIONAL VERTIGO DIAGNOSIS

by  
Sida Zhang, M.A.

Marquette University, 2023

A Thesis submitted to the Faculty of the Graduate School,  
Marquette University,  
In Partial Fulfillment of the Requirements for  
the Degree of Master of Science

Milwaukee, Wisconsin

December 2023

## ABSTRACT

### IMPROVING BENIGN PAROXYSMAL POSITIONAL VERTIGO DIAGNOSIS

Sida Zhang, M.A.

Marquette University, 2022

Benign Paroxysmal Positional Vertigo (BPPV) is one of the most common causes of dizziness. Especially for people over 45, the risk of BPPV is substantial. On the other hand, BPPV is often misdiagnosed and may require expensive examinations. This thesis introduces a prediction model based on machine learning to quickly, inexpensively, and accurately diagnose BPPV. The thesis starts by introducing BPPV and the statistics of BPPV misdiagnosis. Then, a patient survey is introduced. The patient survey includes 50 BPPV-related questions, which are used as training data for the machine learning model. Logistic Regression, Decision Tree, and Naïve Bayes were compared for machine learning models and their results were discussed. Three machine learning approaches are explored, logistic regression, decision tree, and naïve Bayes with cross validation accuracies of 89.8%, 81.9%, and 75.1%, respectively.

## **ACKNOWLEDGMENTS**

Sida Zhang, M.A.

I would like to thank my parents who supported me and gave me encouragement during the whole time of this work.

## TABLE OF CONTENTS

ABSTRACT.....	i
ACKNOWLEDGMENTS .....	ii
TABLE OF CONTENTS.....	iii
LIST OF TABLES .....	v
LIST OF FIGURES .....	vi
Chapter 1 Introduction .....	1
1.1 Background.....	2
1.1.1 Benign Paroxysmal Positional Vertigo .....	2
1.1.2 Motivation.....	3
1.1.3 Common Symptoms of BPPV .....	4
1.1.4 Diagnostic Methods for BPPV .....	5
1.2 Overview of Thesis .....	6
Chapter 2 Background for BPPV .....	7
2.1 Prior Work .....	7
2.2 Description of BPPV .....	10
2.3 Machine Learning Algorithms .....	11
2.3.1 Candidate Algorithms .....	12
2.3.2 Logistic Regression Classifier .....	13
2.3.3 Naïve Bayes Classifier .....	16
2.3.4 Decision Tree Classifier.....	18
2.3.5 Cross-validation.....	20
Chapter 3 Survey Process .....	22
3.1 Aim .....	22
3.2 Structure .....	23
3.2.1 Questions.....	23
3.2.2 Scenario.....	24
3.3 Improvements of Patient Survey.....	25

3.3.1 Survey Simplification.....	26
3.3.2 In-survey Tutorial.....	26
3.3.3 Descriptions of Symptoms .....	28
3.4 Survey Questions.....	29
Chapter 4 Results .....	33
4.1 Data Analysis .....	33
4.2 Machine Learning Results.....	35
4.3 Discussion .....	36
Chapter 5 Conclusion and Future Work .....	38
Bibliography .....	40
Appendix A.....	44

**LIST OF TABLES**

Table 1 Survey Questions .....	29
Table 2 Cross-validation result .....	35

## LIST OF FIGURES

Figure 1 Cumulative incidence of BPPV of different ages .....	3
Figure 2 Inner ear anatomy (Source: Tetiana Lazunova with permission).....	11
Figure 3 Logistic distribution.....	14
Figure 4 Decision Tree Structure .....	18
Figure 5 Age distribution of 40 patients.....	34
Figure 6 Gender of all patients.....	34
Figure 7 Medical examination results of male and female.....	35
Figure 8 Home page.....	45
Figure 9 The welcome page and generate patient ID.....	46
Figure 10 Summary of the survey and summary of the first section.....	47
Figure 11 Instruction page of the first section.....	48
Figure 12 First question in the first section.....	49
Figure 13 Second question in the first section .....	50
Figure 14 Third question in the first section .....	51
Figure 15 4 <sup>th</sup> question in first section.....	52
Figure 16 5 <sup>th</sup> questions in first section .....	53
Figure 17 6 <sup>th</sup> questions in first section .....	54
Figure 18 7 <sup>th</sup> questions in first section .....	55
Figure 19 8 <sup>th</sup> questions in first section .....	56



Figure 20 9 <sup>th</sup> question in first section .....	57
Figure 21 10 <sup>th</sup> question in first section .....	58
Figure 22 Summary of second section and definition of necessary medical terms.....	59
Figure 23 Definition of four dizziness .....	60
Figure 24 First question in second section .....	61
Figure 25 Second question in second section.....	62
Figure 26 Third question in second section.....	63
Figure 27 4 <sup>th</sup> question in second section .....	64
Figure 28 5 <sup>th</sup> question in second section .....	65
Figure 29 Summary of second section .....	66
Figure 30 Introduction of third section.....	67
Figure 31 Scenario 1 of how to answer questions.....	68
Figure 32 Scenario 2 of how to answer questions.....	69
Figure 33 First question of this section .....	70
Figure 34 Second question of this section.....	71
Figure 35 Third question of this section.....	72
Figure 36 4 <sup>th</sup> question of this section .....	73
Figure 37 5 <sup>th</sup> question of this section .....	74
Figure 38 6 <sup>th</sup> question of this section .....	75
Figure 39 Summary of this section .....	76
Figure 40 Introduction of fourth section .....	77

Figure 41 First question of this section .....	78
Figure 42 Second question of this section.....	79
Figure 43 Third question of this section.....	80
Figure 44 4 <sup>th</sup> question of this section .....	81
Figure 45 5 <sup>th</sup> question of this section .....	82
Figure 46 6 <sup>th</sup> question of this section .....	83
Figure 47 7 <sup>th</sup> question of this section .....	84
Figure 48 8 <sup>th</sup> question of this section .....	85
Figure 49 9 <sup>th</sup> question of this section .....	86
Figure 50 10 <sup>th</sup> question of this section .....	87
Figure 51 11 <sup>th</sup> question of this section.....	88
Figure 52 12 <sup>th</sup> question of this section .....	89
Figure 53 Summary of fourth section.....	90
Figure 54 Introduction of fifth section .....	91
Figure 55 First question of this section .....	92
Figure 56 Second question of this section.....	93
Figure 57 Third question of this section.....	94
Figure 58 4 <sup>th</sup> question of this section .....	95
Figure 59 5 <sup>th</sup> question of this section .....	96
Figure 60 Summary of fifth section .....	97
Figure 61 Introduction of seventh section.....	98

Figure 62 The first question of this section .....	99
Figure 63 The second question of this section .....	100
Figure 64 The third question of this section .....	101
Figure 65 The 4 <sup>th</sup> question of this section .....	102
Figure 66 The 5 <sup>th</sup> question of this section .....	103
Figure 67 The 6 <sup>th</sup> question of this section .....	104
Figure 68 The 7 <sup>th</sup> question of this section .....	105
Figure 69 The 8 <sup>th</sup> question of this section .....	106
Figure 70 The 9 <sup>th</sup> question of this section .....	107
Figure 71 The 10 <sup>th</sup> question of this section .....	108
Figure 72 Summary of this section .....	109
Figure 73 Introduction of last section.....	110
Figure 74 The 1 <sup>st</sup> question of this section.....	111
Figure 75 Questions in seventh section.....	112
Figure 76 End page of the patient survey.....	113

## Chapter 1 Introduction

Dizziness is a widespread issue, particularly among the elderly. Approximately 30% of individuals over 60 and 50% of those over 85 have reported vertigo or dizziness [1]. Data from the Hearing and Balance Clinic reveals that over 90 million Americans require medical attention for balance and dizziness problems [1,2]. Dizziness/vertigo is the second most frequently reported patient complaint, yet patients frequently disregard these symptoms [3]. The Hearing and Balance Clinic found that more than 90% of those suffering from balance and dizziness disorders never receive a diagnosis from relevant specialists such as audiologists, otologists, otolaryngologists, or neurologists [3].

Benign Paroxysmal Positional Vertigo (BPPV) is the leading cause of dizziness, but a comprehensive diagnostic method for BPPV, described in Section 1.2.1, requires significant medical resources and time. Additionally, patients may struggle to describe their BPPV symptoms accurately, leading to misdiagnoses.

This thesis addresses the challenges of BPPV diagnosis accuracy and cost by introducing a machine learning-based method utilizing a patient-facing electronic survey. The contribution of this thesis is an upgraded patients' survey. The new survey builds upon previous work [4] by incorporating scenario-based questions, more targeted inquiries, and eliminating redundant questions. The results of the survey also reveal improved diagnostic accuracy, with a Logistic Regression Classifier achieving an accuracy of 89.8%, surpassing the previous accuracy of 74% [4]. The Decision Tree and

Naïve Bayes models also showed improved accuracy at 81.9% and 75.1% respectively, compared to previous accuracy of 70% and 72% [4].

## **1.1 Background**

### **1.1.1 Benign Paroxysmal Positional Vertigo**

BPPV is a peripheral vestibular disorder caused by loose crystals in the inner ear that are affected by gravity [3]. It presents as recurrent, short-term vertigo and uncontrolled eye movements (nystagmus). Although BPPV is typically self-limiting, recovery is not guaranteed, and relapses are possible. Diagnosis of BPPV requires costly medical resources [2], leading to variations in diagnostic methods across countries and differing epidemiology between nations.

The annual prevalence of BPPV is estimated at 1.6%, with a lifetime prevalence of 2.4% [5]. BPPV accounts for 20-30% of cases of vestibular vertigo, with a gender ratio of 1:2 to 1:1.5 [5]. The incidence rate increases with age, particularly after 40, as illustrated in Figure 1 [5]. The incidence of BPPV in individuals under 35 is close to zero, but rapidly increases for those over 40 and especially for those over 70.

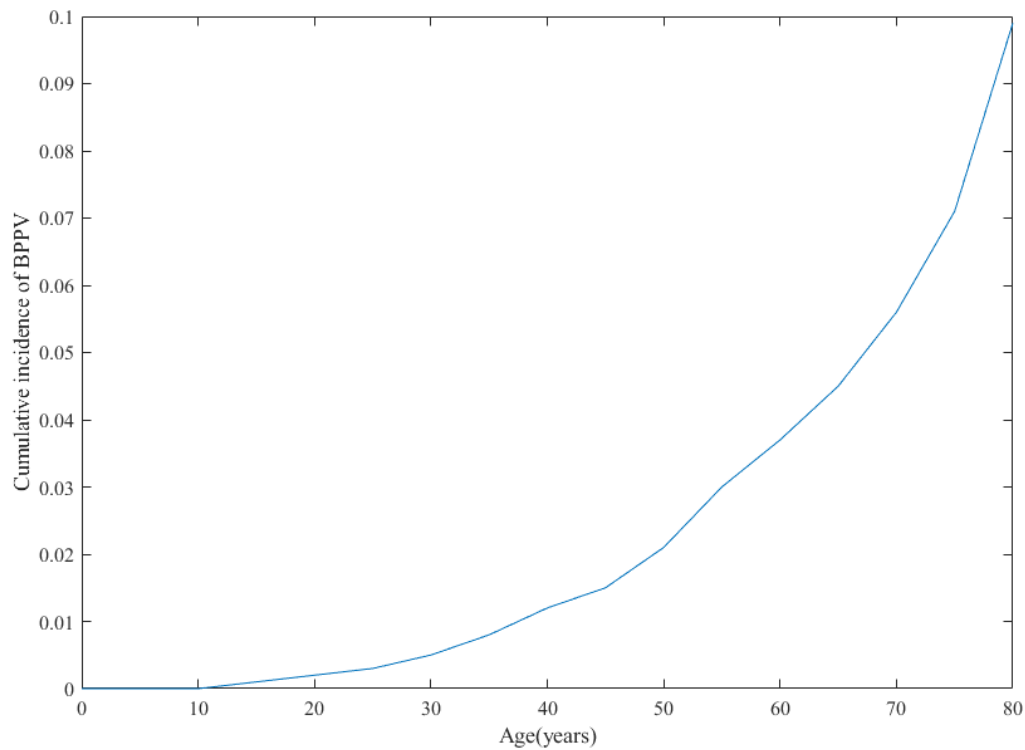


Figure 1 Cumulative incidence of BPPV of different ages

### 1.1.2 Motivation

The goal of this research is to decrease diagnostic costs and complexity, prevent misdiagnosis, and improve the accuracy of the predictive model. To achieve this, an electronic patient survey has been proposed to simplify diagnosis. The results from the patient survey and a medical examination are used to train a machine learning models for BPPV prediction.

BPPV has a high rate of misdiagnosis, as seen in a study by Qian et al. where 48 out of 60 BPPV cases were misdiagnosed [1]. These misdiagnosed cases underwent standard diagnostic procedures, such as CT scans, MRI, and cerebrovascular exams,

resulting in an average misdiagnosis cost of over \$1,000 [1]. Hence, this research aims to introduce methods that lower the rate of misdiagnosis.

Traditional diagnostic methods for BPPV can be complex (auditory and etiological exams), costly (CT and MRI scans), and time-consuming (static or dynamic postural tracing tests). Previous studies have shown that a patient's medical history and significant symptoms hold the key to diagnosing BPPV. Machine learning can help reduce costs by rapidly classifying potential cases, and machine learning and the electronic patient survey can minimize the time needed for accurate BPPV diagnosis.

### **1.1.3 Common Symptoms of BPPV**

According to research conducted at Johns Hopkins, the primary symptom of BPPV is vertigo, a sensation of spinning which arises when a patient alters their head position [6]. This vertigo can cause additional problems, such as temporary loss of balance and the risk of falling when a patient moves their head, such as getting out of bed, or tilts their head forwards or backwards while walking. The duration of symptoms without medical treatment can persist for a varying amount of time, from days to weeks or indefinitely [6]. In some instances, the condition may resolve on its own.

As BPPV is an inner ear condition, ear health is also a significant symptom. Brevern et al. conducted a study with over 1000 patients and found that 10% of the patients had secondary BPPV [5]. Secondary BPPV can be caused by factors such as head or ear trauma, other ear conditions, migraines, and intubation [5]. These factors can

impact ear health, causing patients to experience inner ear pain. In the patient survey, 38 out of 50 questions pertained to symptoms, including symptom duration, ear condition, and typical symptom scenarios.

#### **1.1.4 Diagnostic Methods for BPPV**

To diagnose BPPV, the patient's medical history is gathered, and a series of physical exams are conducted, including:

- Vestibular function examinations such as Video-Nystagmography (VNG) and Rotational Chair Tests (RCT) to evaluate the patient's condition through eye movements. BPPV affects a patient's sense of balance, and VNG assesses this by monitoring eye movements.
- An audiology exam to assess hearing ability through tests with different sounds, pitches, and frequencies. This includes a pure tone audiometry test, a word recognition test, and a tympanometry test. The pure tone audiometry measures the patient's frequency range while wearing earphones, while the word recognition test evaluates their ability to understand noisy speech. The tympanometry test detects structural conditions in the ear, such as ossicle damage, inner ear tumors, and wax buildup.
- Imaging techniques, including x-rays, ultrasound, CT scans, MRI, and nuclear imaging, to visually detect dislodged otoconia, which is the root cause of BPPV.



- Balance function tests, including VNG and vestibular evoked myogenic potentials (VEMP), to evaluate a patient's sense of balance by testing muscle activity when exposed to sound from different directions.

## **1.2 Overview of Thesis**

This thesis introduces an improved patient survey and machine learning models to optimize the cost and time required for diagnosing BPPV. Chapter 2 overviews related works and offers a comprehensive analysis of BPPV, including its pathogenesis and typical symptoms. The chapter also explains the three machine learning methods applied in this study.

Chapter 3 details the patient survey process, including its purpose and structure. Chapter 4 evaluates prior work performed by our group and highlights the unique contributions of this thesis, such as a simplified language, more precise symptom descriptions, and an in-survey tutorial to prevent misunderstandings and improve symptom reporting accuracy.

Chapter 5 validates the ideas presented in Chapter 4 through a verification process. The final chapter concludes the entire thesis, offering recommendations for future research and discussing the limitations of the current study.

## Chapter 2 Background for BPPV

### 2.1 Prior Work

This section highlights prior research on survey-based disease classification. Auramo et al. developed an Expert System (ES) for the diagnosis of otoneurological conditions [12]. It gathers patient medical history and clinical measurement data, emulating a specialist's evaluation to determine the patient's diagnosis. For instance, migraine and BPPV both result in dizziness, but they differ in their triggering methods and symptom duration. The ES can differentiate between the two based on these distinct characteristics. Mira et al. created an ES model to classify different types of dizziness [13]. It comprises basic information about a range of dizziness-causing diseases to aid in their classification. When a patient seeks medical attention for dizziness, the doctor can use the ES model presented in [13] to make a diagnostic decision. Over 200 dizziness cases have been tested, and this ES model is widely utilized in the otoneurological field.

ONE is an expert system for diagnosing vertigo [14]. Its purpose is to provide educational support and implement a database of patient information. The ONE database contains medical history, physical symptoms, and exam results of patients who exhibit vertigo-related symptoms. Kentala et al. used pattern recognition on the ONE database, weighing and scaling vertigo-related symptoms, physical symptoms, and exam results to classify vertigo-related diseases [14]. The most probable disease is identified based on disease profiles, and fuzzy logic was employed to handle missing information and uncertainties. The accuracy of ONE was compared with that of physicians, with the mean

physician accuracy being 69% and ONE's accuracy being 65% [14].

Bansal developed Computer-Aided Diagnosis in Neurotology (CADINO), which encompasses over 100 causes of dizziness and aids clinicians in making a diagnosis [15]. CADINO is not an AI agent, but a collection of characteristics for different diseases causing dizziness. Clinicians make decisions based on these characteristics. Quick Medical Reference (QMR), a computer-assisted consultation service, also achieves similar diagnostic sensitivity as an assistant service [16]. QMR provides valuable, alternative suggestions and was rated as helpful for education [16]. [12], [13], [15]. [16] provides the foundational understanding of diagnosing vertigo, meaning that a set of symptom attributes can be used to classify it. These four expert system models demonstrate that the various causes of dizziness, differing in symptoms, can be classified by a well-trained model. A questionnaire based on the characteristics of the expert system can be used to gather training data.

Yu et al. created a questionnaire-based learning model to diagnose vertigo [17]. Over 1600 patients participated in the survey. Several models were used to classify five different types of vertigo, and nine learning algorithms were tested. The light gradient boosting machine performed best with an accuracy of 93.7% [17].

Feil et al. designed another survey-based learning model to classify six dizziness-related diseases [18]. The classification accuracy was 97.5% for Bilateral Vestibulopathy, 95.3% for Meniere's disease, 93.4% for Benign Paroxysmal Positional Vertigo, 97.5% for

Downbeat Nystagmus Syndrome, 88.3% for Vestibular Migraine, and 96.6% for Phobic Postural Vertigo [18].

Masankaran et al. introduced the Dizziness Handicap Inventory (DHI), which measures a patient's dizziness severity [19]. DHI can differentiate between different types of BPPV, which are divided into three types based on the affected ear canal: AC-BPPV (anterior canal), PC-BPPV (posterior canal), and HC-BPPV (horizontal canal). DHI can aid clinicians in determining the appropriate treatment for each type of BPPV.

Masankaran et al. investigated the performance of machine learning prediction models incorporating DHI. To differentiate between PC-BPPV and HC-BPPV, several machine learning techniques were examined, including random forests, support vector machines, k-nearest neighbors, and Naive Bayes, which were applied to a 25-question survey based on data from 114 BPPV patients. Naive Bayes performed the best with an accuracy of 73.9% [19].

Previous work on BPPV diagnosis by our group was conducted by Fasaie [4] and Richburg [20]. They employed a machine learning prediction approach using patient survey data. Fasaie used an ANN model with an autoencoder that transformed attributes into 22 features, with a reconstruction mean squared error of 0.11 [4]. Logistic regression, naïve Bayes, and decision tree classifiers were used to predict BPPV after correlation feature selection with similar accuracy of 70-74% [4]. Friedland et al. developed a paper survey with 162 questions focused on dizziness perception, migraine symptoms, otologic

problems, and medical test results [27]. Richburg designed three versions of the patient survey, reducing the number of questions to 84 based on Friedland's survey [27] and eliminating low-information gain questions. The third version was used to evaluate the importance of each survey question with little impact on the survey structure. Richburg's research showed that a decision tree with filters or wrappers is effective in identifying BPPV [20]. This thesis presents a new patient survey that provides data for the machine learning model, based on the research of Fasae and Richburg.

## **2.2 Description of BPPV**

BPPV is an inner ear disorder that often leads to vertigo, a type of dizziness where one feels as though the room is spinning. The disorder is caused by dislodged otoconia (crystals) interfering with hair cells in the cupula, as shown in Figure 2, which depicts the anatomy of the inner ear. The otoconia can separate and move from the utricle to the posterior semicircular canal and, in rare cases, to the anterior or horizontal semicircular canal. When a person moves their head, the displaced otoconia activates the hair cells in the cupula, which sense body direction. The activated otoconia may then send incorrect signals to the brain, causing an erroneous perception of balance and resulting in dizziness.

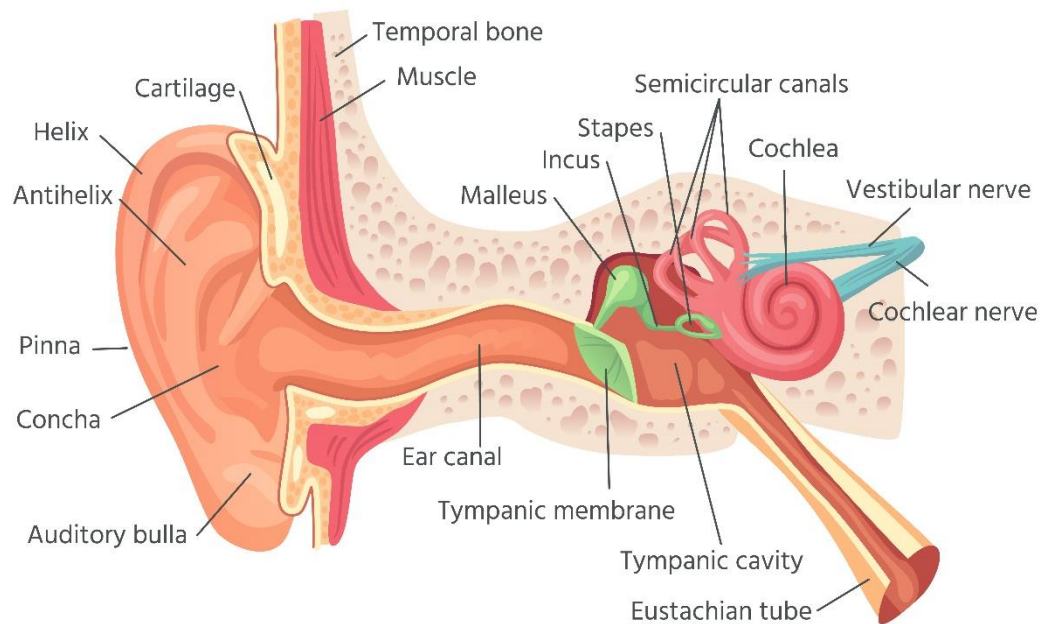


Figure 2 Inner ear anatomy (Source: Tetiana Lazunova with permission)

The dislodged otoconia in the cupula can shift when the patient moves their head and touches the hair cells. As a result, a BPPV episode is often triggered by a change in gravity affecting the patient's head, leading to a sudden and temporary experience of dizziness. Symptoms frequently include nausea, vertigo, lightheadedness, a feeling of floating, loss of balance, and visual hallucinations [21].

### 2.3 Machine Learning Algorithms

Machine learning algorithms can be classified into three groups: supervised, unsupervised, and reinforcement. Supervised learning involves examples with accompanying labels, while unsupervised learning lacks labels. The objective in supervised learning is to establish a mapping between examples and labels. For

unsupervised learning, the goal is to find a compact representation of the data.

Reinforcement learning is similar to supervised learning, but labels are only provided at certain intervals and not for every example. This study employs supervised learning, as each patient's features have labels indicating a diagnosis of BPPV or not. This thesis employs three standard supervised learning algorithms (logistic regression, naïve Bayes, and decision tree) for the BPPV diagnosis problem, which are described below.

### **2.3.1 Candidate Algorithms**

This section outlines the selection of naïve Bayes, Decision Tree, and Logistic Regression algorithms for the study. The survey data collected from BPPV patients consisted of 50 questions and demographic information such as age and gender, resulting in 52 input factors for the machine learning model. The goal was to predict the presence of BPPV. The Decision Tree classifier was preferred over others due to its ease of implementation and data preparation, as all survey questions could be used as tree nodes without the need for normalization or scaling. Furthermore, the visual representation of the tree makes it easy to understand.

On the other hand, the naïve Bayes classifier requires less training data compared to others. In this case, it calculates the posterior probability of a patient having BPPV based on the probability of patients with BPPV, the probability of patients with the same factors (50 survey questions, age and gender), and the probability of patients with the same factors among all BPPV patients. This reduces the amount of data required for

accurate calculation.

Lastly, Logistic Regression was chosen for its simplicity in training and implementation. The model uses each factor and its coefficient to calculate the output and evolves the coefficients during training to arrive at the optimal solution. Additionally, the model displays the positive or negative impact of each factor on the output, making it intuitive to understand.

### **2.3.2 Logistic Regression Classifier**

Logistic regression is a classification method that is used for binary, probabilistic classification [23]. For example, the probability that a person has BPPV based on their answers to a survey. The result is often used for weighted summation with other eigenvalues instead of direct multiplication.

We examine the logistic function, also known as sigmoid function and logistic distribution. The sigmoid function is a continuous probability distribution defined as

$$y = \frac{1}{1 + e^{-z}} \cdot \quad (1)$$

Figure 3 shows the logistic distribution.



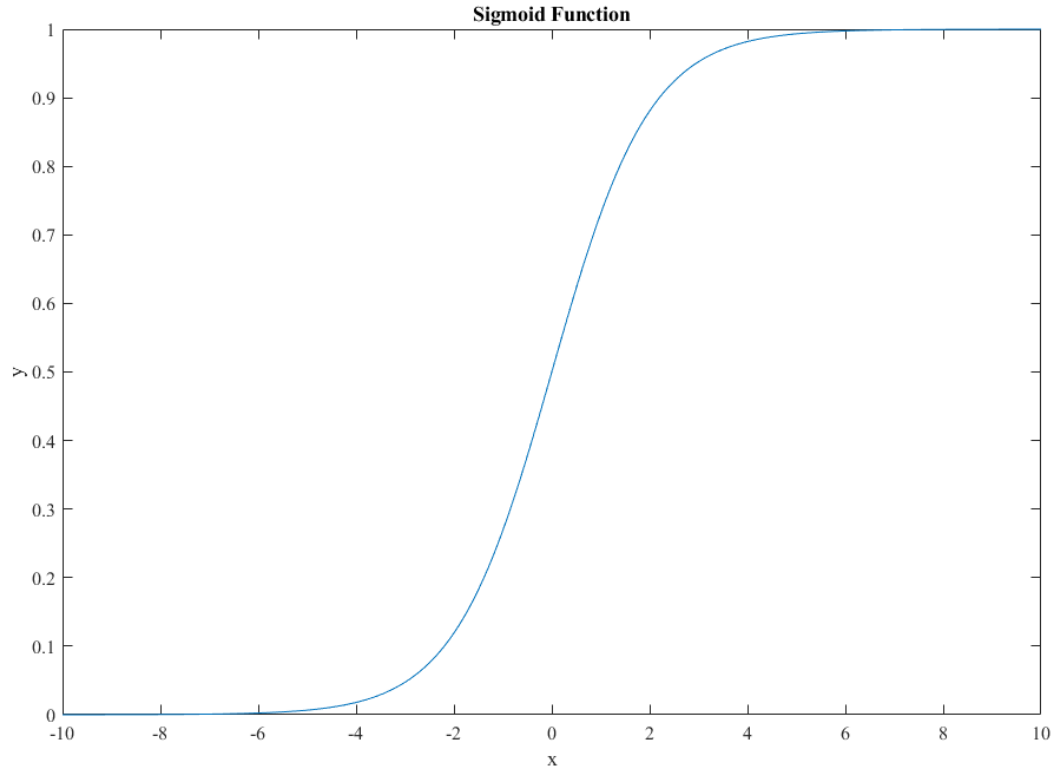


Figure 3 Logistic distribution

As shown in Figure 3, when variable  $z$  is greater than 0,  $y$  is greater than 0.5. We assume  $y$  represents probability. When the probability of  $y$  is greater than 0.5, we assign input  $z$  as label “1”. When probability  $y$  less than 0.5, we assign input  $z$  as label “0”. In binary classification, inputs are a series of parameters that can be written as:

$$z = \omega_0 + \omega_1 x_1 + \omega_2 x_2 + \dots + \omega_n x_n, \quad (2)$$

where  $x_0, x_1, \dots, x_n$  are attributes for  $z$  and  $\omega_0, \omega_1, \omega_2, \dots, \omega_n$  are weights for the attributes.

When training the model, a cost function is needed for labels “1” and “0”. When  $label = 0$ , the cost function is

$$cost = -\ln(1 - h). \quad (3)$$

When  $label = 1$ , the cost function is

$$cost = -\ln(h). \quad (4)$$

For both cases ( $label = 1$  or  $0$ ), the cost function written as,

$$cost = -y^* \ln(h) - (1 - y^*) \ln(1 - h), \quad (5)$$

where  $y^* = label$ .

The training process estimates  $\omega_0, \omega_1, \omega_2, \dots, \omega_n$  to minimize the cost function.

The pseudocode for the Logistic Regression Classifier is shown below.

---



---

Algorithm-1: Logistic Regression

---

Input: Training Data

---

1. Label vector label= [0,1]
  2. For  $i$  from 1 to  $n$
  3. Calculate:  $z = \omega_0 + \omega_1 x_1 + \omega_2 x_2 + \dots + \omega_n x_n$
  4. Based on the value  $z$  calculated from step 1 calculate:
  5. 
$$y = \frac{1}{1+e^{-z}}$$
  6. Minimize cost function
  7. 
$$cost = -y^* \ln(h) - (1 - y^*) \ln(1 - h)$$
  8. if  $P(1|d_j) > 0.5$ ,
  9. label=1
  10. otherwise assign label 0.
-

### 2.3.3 Naïve Bayes Classifier

The Naïve Bayes Classifier uses probability statistics to classify samples. The combination of prior probability and posterior probability in a naïve Bayes classifier avoids the subjective bias of using only prior probability [24]. Because of a solid mathematical foundation, the misjudgment of naïve Bayes Classifier is low [24]. The Bayesian classification algorithm shows high accuracy when the data set is large, and the algorithm itself is straightforward [25].

The Bayes function calculates the posterior probability. The Bayes function solves the problem often encountered in real life. The following is the Bayes Formula:

$$P(A|B) = \frac{P(A)P(B|A)}{P(B)}. \quad (6)$$

The posterior probability of A can be calculated by the probability of A, the posterior probability of B, and the probability of B. We consider B as a factor of A. When A determined by a series of factors  $B_1, B_2, B_3, \dots, B_n$ , the posterior probability of A can be calculated as

$$P(A|B_1, B_2, B_3, \dots, B_n) = \frac{P(A) \prod_i^n P(B_i|A)}{\prod_{i=1}^n P(B_i)}, \quad (7)$$

which is determined by probability of A, probability of B, and posterior probability of B.

In BPPV, for example, assuming symptoms and triggering methods are two factors of whether a patient has BPPV, we assign them as  $B_1$  and  $B_2$  and A is “has BPPV”. Then, the posterior probability becomes  $P(\text{has BPPV}|B_1, B_2)$ . Based on formula (7), the

components for calculating the probability of a patient having BPPV are the probability of all patients having BPPV, the probability of BPPV patients who have the same condition  $B_1$  and  $B_2$ , and probability of patients who have the same conditions  $B_1$  and  $B_2$ . These three components can be calculated from the dataset.

The following is the pseudocode of Naïve Bayes Classification.

---



---

#### Algorithm-2: Naïve Bayes Classification

---

Input: Training dataset T,

$F = (f_1, f_2, f_3, f_4, \dots, f_n)$  // value of the predictor variable in the testing dataset.

Output:

A class of testing dataset.

---

Steps:

1. Read the training dataset T.
  2. Calculate the mean and standard deviation of the predictor variables in each class.
  3. Repeat
  4. Calculate the probability of  $f_i$  using the gauss density equation in each class.
  5. Until the probability of all predictor variables  $(f_1, f_2, f_3, f_4, \dots, f_n)$  has been calculated.
- 

6. Calculate the likelihood for each class.

7. Get the greatest likelihood.

---

### 2.3.4 Decision Tree Classifier

A decision tree is an algorithm used for classification and regression. It has a tree-shaped structure. As shown in Figure 4, starting from the root node, the decision tree tests a feature sample and assigns the instance to its child nodes according to the test results. Each child node corresponds to a value of the feature, so the samples are tested and assigned recursively until the leaf node is reached. Finally, the sample is assigned the leaf node's class [26].

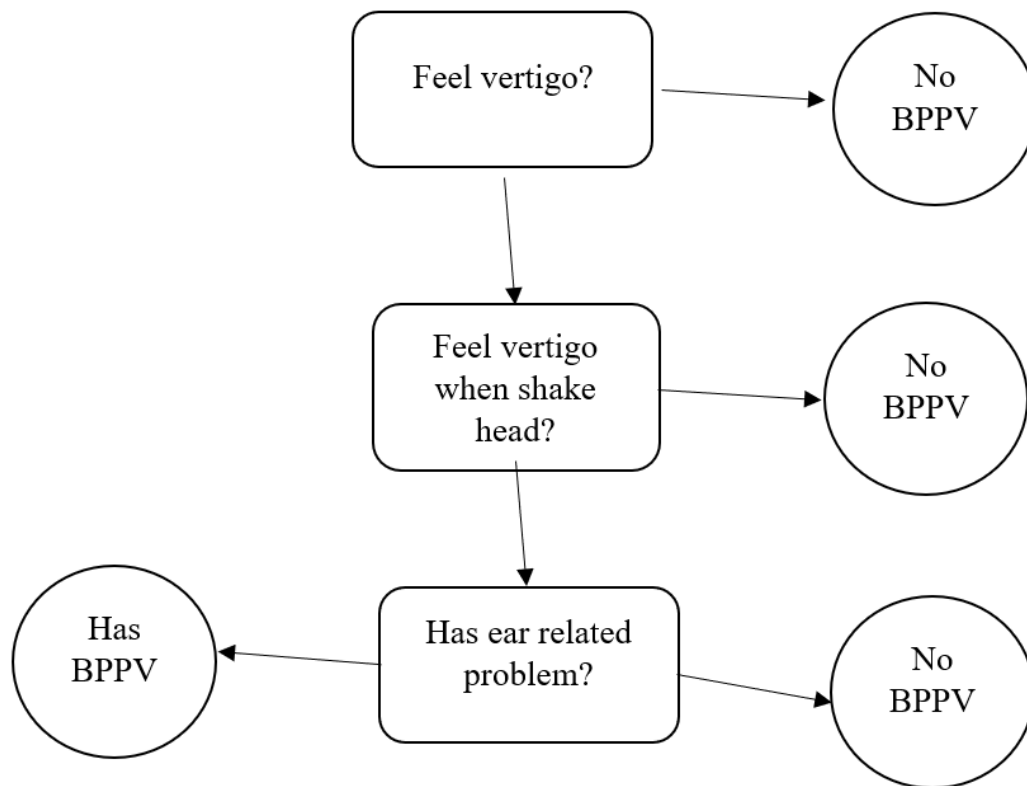


Figure 4 Decision Tree Structure

In decision tree classification, "find best split" refers to the process of identifying

the attribute and its corresponding value that produces the highest information gain (or the lowest impurity) when we use it to split the data at a particular node.

The information gain is a measure of the reduction in entropy (or impurity) achieved by splitting the data on a particular attribute. The attribute with the highest information gain is considered the best split because it provides the most discriminatory power to separate the different classes in the dataset.

The decision tree algorithm iterates over all attributes, and their possible values to determine that split that produces the highest information gain. Once the best split is identified, the data is partitioned into two or more subsets based on the split, and the process is repeated recursively on each subset until a stopping criterion is met, such as a maximum tree depth or a minimum number of samples at each leaf node. The quality of the split can have a significant impact on the performance of the decision tree classifier, and finding the best split is a critical step in building an accurate and efficient decision tree model.

The pseudocode of a decision tree classifier is shown below.

---

---

#### Algorithm-3: Generate a Decision Tree

---

1. GenDecTree (Sample S, Features F)
2. If stopping\_condition(S, F) = true **then**
3.     Leaf = createNode()
4.     leafLabel = classify(s)
5.     **return** leaf

6.  $root = createNode()$
  7.  $root.test\_condition = findBestSpilt(S,F)$
  8.  $V = \{v | v \text{ a possible outcome of } root.test\_condition\}$
  9. For each value  $v \in V$ :
  10.  $S_v = \{s | root.test\_condition = v \text{ and } s \in S\};$
  11.  $Child = TreeGrowth(S_v, F)$
  12. add child as descent of root and label the edge  $\{root \rightarrow child\}$  as  $v$
  13. return root
- 

### 2.3.5 Cross-validation

Cross-validation is a method used to evaluate the performance of a machine learning model by using a subset of the available data to train the model and a different subset to test the model. The main idea behind cross-validation is to use multiple rounds of training and testing to get a more accurate estimate of the model's performance.

K-fold cross-validation is the most popular cross-validation method. In k-fold cross-validation, based on the amount of data, the data is divided equally into k folds. Then, the learning model is trained and tested k times. In every round, a different fold is used as the test set. The remainder of the k-1 folds are the training set. The performance (such as accuracy or error rate) of each round is recorded.

After k rounds of training and testing, the performance metrics from each round are

averaged to obtain a more robust estimate of the model's performance. This approach is beneficial because it allows the use of all available data for training and testing and helps to avoid overfitting by testing the model on data that it has not seen during training.

Other forms of cross-validation include leave-one-out cross-validation, which involves training the model on all but one of the data points and testing it on the remaining point, and stratified cross-validation, which ensures that the distribution of classes is preserved in each fold. Overall, cross-validation is a powerful tool for evaluating the performance of a machine learning model and is widely used in practice to select and tune models.



## Chapter 3 Survey Process

### 3.1 Aim

The patient survey used in this study was designed based on the symptoms and characteristics of BPPV as described in section 2.2. The questions in the survey are based on previous studies [20], [27]. Friedland et al. developed a 162-question paper-based questionnaire [27], which focused on dizziness perception, migraine symptoms, otologic problems, and medical test results. Richburg et al. [20] then reduced the number of questions to 84 and further to 41, removing those deemed unimportant through analysis (by calculating the information gain from each question). The survey was further updated with questions based on features collected by Siermala et al. [28]. The third version of Richburg's survey was used to evaluate the importance of each question, with little change made to the survey structure.

The details of the updates made to the survey questions in this thesis are discussed in Chapter 4. The survey is implemented as an Android-based app and includes questions related to symptoms and disease characteristics. All questions of the new survey are shown in Appendix A. The answers provided by patients in the survey serve as the data used to train the machine learning models.

The survey generates a database of answers to all questions, and the goal of the machine learning model is to match the clinician's diagnosis.

## **3.2 Structure**

The patient survey is composed of seven parts, which are the perceptual description of the symptoms, the self-judgment of the symptoms (the patient's self-diagnosis according to the medical definitions), the duration of the symptoms, the triggering methods, ear-related problems, migraine, and related medical history. There are 50 questions, and at the end of each section there is a summary paragraph to confirm the patient's answers.

### **3.2.1 Questions**

The first part (ten questions) investigates the patient's symptoms. These ten questions were summarized by Dr. Friedland from the Medical College of Wisconsin through the patient's self-description when he treated BPPV patients. Most scenarios of questions designed mainly summarized based on the patients' self-description. The questions are general and colloquial. The purpose of this section is to eliminate the lack of medical knowledge that may cause patients to misunderstand the questions.

The second part (five questions) asks about four specific symptoms of vertigo. Patients choose their symptoms through medical definitions (the medical definitions are shown at the beginning of this section). The medical definition may cause misunderstanding of symptoms.

The third part (six questions) investigates the duration of the patient's symptoms. The duration is divided into a few minutes, 20 minutes to an hour, within twelve hours,

within one day, and lasts longer than one day. This part helps to determine the duration of the patient's symptoms.

The fourth part (12 questions) investigates the triggering methods of the patient's symptoms. Since BPPV is an ear-related disease, moving the head in different directions, strengths, and frequencies will trigger vertigo [3]. Moreover, different movements can also reflect the severity of BPPV. Therefore, the 12 questions in the fourth part not only ask whether different actions will cause vertigo, but also ask whether the action will make the symptoms worse.

The fifth part (five questions) asks about the specific conditions of the patient's ears. The main questions are whether the patient feels pain in the ears, whether they hear specific sounds when vertigo occurs, and whether the two ears would have similar symptoms.

The sixth part (10 questions) investigates the migraine-related symptoms. These include the problem of migraine symptoms, whether a migraine has been diagnosed before, and whether dizziness occurs under certain circumstances. Since the symptoms of migraine are like BPPV, this part is used to distinguish these two diseases.

The seventh part (two questions) investigates the patient's medical history (chemotherapy and hip or knee replacement surgery)

### **3.2.2 Scenario**

The patient presses the “Start” button to enter the survey and generate a user's ID

number by the system. The user's ID number is used in the database to sort and identify each patients' answer. The welcome interface tells the user the total number of questions and reminds the user to answer carefully. In the first part, the patient chooses very similar, similar, unrelated, dissimilar, and very dissimilar through 10 questions about different symptom descriptions. At the beginning of the second part, the user is provided four different medical definitions of vertigo, and in the follow-up questions, they select the one that best describes their symptoms. Then, they complete all the questions and answer them in turn. Before the beginning of each part, the user will be informed of the main content and quantity of the questions. At the end of each part, a summary page is generated to help the user to confirm that there is no incorrect answer in the current section. After going over all questions, the system will automatically record the answers to all questions, generate a database, and send it to the researchers by email.

### **3.3 Improvements of Patient Survey**

This chapter presents enhancements made to the patient survey. The goal is to gather more precise information and eliminate redundant or unhelpful questions. The improvements include a clearer description of certain questions, and improvement in the wording of the survey. The following subsections outline the main methods used to improve the survey, including simplification of the survey structure, improvement in question wording, addition of an in-survey tutorial, and mitigation of inaccurate symptom reporting.

### **3.3.1 Survey Simplification**

To improve the patient survey, simplification of language and elimination of redundant questions was necessary. Complex and lengthy descriptions could impact the user's accuracy in judging symptoms and recalling medical history. To simplify the survey, language was made simpler, sections were reordered, and duplicate questions were removed. Language simplification involved reducing lengthy explanations, reordering sentences to simplify them, and eliminating duplicated explanations. For instance, in the explanation of the four medical terms related to vertigo, only the definitions were kept, while examples were omitted to avoid misunderstandings.

In the fifth section (conditions of the patient's ears), one question was deleted. This question asked that "Do you have pain in both ears equally?". Because the main reason of BPPV is dislodged otoconia, equal conditions happen to both ears are rarely appearing.

### **3.3.2 In-survey Tutorial**

Benign paroxysmal positional vertigo (BPPV) is a common condition that affects the inner ear, resulting in brief episodes of dizziness or vertigo. Patients experiencing BPPV often visit doctors to seek medical attention. However, patients may not clearly understand their symptoms, which can lead to misunderstandings about their condition.

This lack of understanding can lead to inaccurate descriptions of symptoms and misinterpretation of medical definitions. For example, patients may use different words or

phrases to describe their symptoms, making it difficult for doctors to accurately diagnose and treat the condition. In addition, patients may not understand medical terms used by doctors, which can lead to confusion and further misunderstanding.

To address these issues, the survey includes sections designed to provide necessary explanations and guidance. These sections may include information about BPPV and its symptoms, as well as descriptions of medical terms and definitions used to diagnose and treat the condition. By providing this information, patients can better understand their symptoms and communicate them effectively to their doctors. This can lead to more accurate diagnoses and better treatment outcomes for patients with BPPV.

In Section 2, four types of vertigo are introduced with a dedicated page for patients to learn the definitions, promoting a better understanding of medical terms. Additionally, Section 3, which inquires about symptom duration, presents two distinct scenarios to clarify duration measurement for the patient. For instance, if a patient experiences dizziness for a minute after turning over in bed and again a few minutes later, the duration of their symptoms would be considered a minute, not a few minutes.

In Section 3, the duration of patients' symptoms was asked. The duration of their symptoms from a few seconds to one or two days. Six questions in this section ask different interval duration, which are "seconds to a few minutes", "between 20 minutes and an hour", "more than an hour but less than 12 hours", "more than 12 hours but not more than 1 day", and "more than a day". If a patient's duration of symptoms lasts

several hours, the patient should choose “Yes” on the question “Does your symptoms last more than an hour but less than 12 hours”. However, in this case, the duration of a couple of hours includes “a few minutes” and “20 minutes to an hour” and question ask about “a few minutes” comes before question ask that “Does your symptoms last more than an hour but less than 12 hours”. Thus, patients may select the wrong answer. Therefore, two tutorial pages show this possible scenario at the beginning of this section.

### **3.3.3 Descriptions of Symptoms**

In some cases, patients may still have difficulty accurately describing their symptoms despite the in-survey tutorial. When this happens, a summary of common symptoms reported by other patients with similar conditions can be used as a substitute for a doctor's explanation. This approach can help patients better understand their symptoms and provide doctors with valuable information to aid in diagnosis and treatment.

The new patient survey includes a section specifically designed to address this issue. This section was compiled by Dr. Friedland of the Medical College of Wisconsin and summarizes common symptoms reported by patients with BPPV. The section consists of 10 questions, each based on a patient's statement about their symptoms. Patients will select the appropriate level of similarity (very similar, similar, unrelated, dissimilar, or very dissimilar) for each question.

For example, one question may ask about the duration of a patient's symptoms,

with options ranging from a few seconds to several minutes. Another question may ask about the severity of the symptoms, with options ranging from mild to severe. By answering these questions, patients can better understand their symptoms and how they compare to those reported by other patients with BPPV.

This approach can be particularly useful for patients who may have difficulty communicating their symptoms to their doctor due to language barriers or other factors. By providing a summary of common symptoms, patients can still receive valuable information about their condition and potential treatment options. Ultimately, this can lead to better outcomes for patients with BPPV and other conditions.

### 3.4 Survey Questions

This section lists all the survey questions used in the patients' survey. The first survey section has 10 questions which mainly summarized based on the patients' self-description. Patients should scale their similarity to the scenarios in each question which are "very similar", "similar", "neither dissimilar or similar", "dissimilar", and "very dissimilar". Then, except for the first question in the second section, choose a most likely symptom, all the questions in the rest part are choosing "yes" or "on".

Table 1 Survey Questions

<b>Question Number</b>	<b>Question Text</b>
Section1 q1	My dizziness often comes when lying down or turning in bed. It



Question Number	Question Text
	feels like I am spinning or moving. The dizziness lasts less than a minute. This has happened on many days or weeks.
Section1 q2	My dizziness comes at any time. I could be sitting still, and it happens. I feel lightheaded and woozy. It lasts seconds to minutes.
Section1 q3	My dizziness often comes when moving my head such as lying down in bed, tilting my head back, or reaching and bending. It is a strong dizzy feeling. The strong feeling lasts less than a minute, but I do not feel well or normal for longer.
Section1 q4	My dizziness comes when I sit or stand up. I feel lightheaded like I might pass out. It lasts anywhere from a few seconds to a few minutes.
Section1 q5	My dizziness usually occurs when I am walking. It is made worse if I turn my head left and right. It feels like I drift from side to side.
Section1 q6	My dizziness is always there. I feel better when lying in bed. I feel worse when doing things like walking down aisles in a store or going down long hallways.
Section1 q7	My dizziness feels like I am unsteady. It is worse in the dark. I feel like I drift to the side when walking.
Section1 q8	My dizziness comes on suddenly without warning. It lasts hours but not more than a day. The dizziness makes me feel like throwing up. When I get the dizziness, I cannot do anything except sit still or lie down.
Section1 q9	My dizziness comes at any time. It can last hours or even days. I often get a headache when I am dizzy. I feel very tired and often lie down in the dark.
Section1 q10	I get short episodes of dizziness. The dizziness comes when I move. This happens many times in a day or week.
Section2 q1	Choose type of dizziness that best characterizes your condition. Using the definitions noted on the prior page, which one of the following most closely resembles your main form of dizziness.
Section2 q2	Have your symptoms occurred once or more than once?
Section2 q3	With your symptoms have you had nausea or felt queasy?
Section2 q4	During your symptoms have you ever had blurry vision?
Section2 q5	During your symptoms have you ever had double vision?
Section3 q1	Do your symptoms last between seconds to a few minutes?
Section3 q2	Do your symptoms last between 20 minutes and an hour?
Section3 q3	Do your symptoms last more than an hour but less than 12 hours?
Section3 q4	Do your symptoms last more than 12 hours, but not more than 1

Question Number	Question Text
	day?
Section3 q5	Do your symptoms last more than a day?
Section3 q6	Is your symptom currently with you 24 hours a day, never stopping?
Section4 q1	Is your symptom typically made worse or triggered by sitting up or standing up?
Section4 q2	Is your symptom typically made worse or triggered by reaching or bending?
Section4 q3	Is your symptom typically made worse or triggered by tilting your head back?
Section4 q4	Is your symptom typically made worse or triggered by lying down in bed?
Section4 q5	Is your symptom typically made worse or triggered by rolling over or turning in bed?
Section4 q6	Is your symptom typically made worse or triggered by turning your head while walking?
Section4 q7	Is your symptom typically made worse or triggered by supermarket aisles?
Section4 q8	Is your symptom typically made worse or triggered by seeing things go past over and over like scrolling on your phone or watching a train pass?
Section4 q9	Is your symptom typically made worse or triggered by loud noises?
Section4 q10	Is your symptom typically made worse or triggered by automobile rides?
Section4 q11	Is your symptom typically made worse or triggered by walking on uneven ground?
Section4 q12	Is your symptom typically made worse or triggered by driving a car at night?
Section5 q1	Do you have ear pain?
Section5 q2	Do you get an ear infection at least once a year?
Section5 q3	Do you have pain in ONE EAR ONLY or ONE EAR MORE THAN THE OTHER?
Section5 q4	Do you hear a ringing, buzzing, hissing, or other noise in ONE EAR ONLY or ONE EAR MORE THAN THE OTHER?
Section5 q5	Do you hear a ringing, buzzing, hissing, or other noise in BOTH EARS EQUALLY (or in your head)?
Section6 q1	Have you had a total of 5 or more bad headaches in your lifetime?
Section6 q2	Have you ever had a headache that throbs or pulses?

<b>Question Number</b>	<b>Question Text</b>
Section6 q3	Have you ever had increased sensitivity to light with a headache?
Section6 q4	Have you ever had increased sensitivity to sounds with a headache?
Section6 q5	Have you ever had increased sensitivity to smells with a headache?
Section6 q6	Have you ever had nausea or vomiting with a headache?
Section6 q7	Have you ever had your symptoms associated with a headache?
Section6 q8	Have you ever been diagnosed with migraine headaches?
Section6 q9	Have you ever been diagnosed with ocular or retinal migraines (means a temporary change in vision that may come with a headache)?
Section6 q10	Did you get carsick as a child?
Section7 q1	Have you had a hip or knee replacement?
Section7 q2	Have you had chemotherapy?

## Chapter 4 Results

### 4.1 Data Analysis

This section introduces the results of the machine learning prediction models. The data used for training the machine learning model are collected from 40 patients who visited Medical College of Wisconsin from April to September in 2021 who were suspected of having BPPV. All patients were offered the opportunity to take the survey. A database, including all survey answers, was generated. The label (whether they have BPPV) was determined from a medical examination. Data were collected from human subjects under approved institutional review board agreements. The data stored in the results database was anonymized.

All 40 patients' age distribution is shown in Figure 4 (orange line is the positive rate of BPPV). The interval of age from 67 to 81 has the biggest population, which is 18 cases and 45% of all patients.

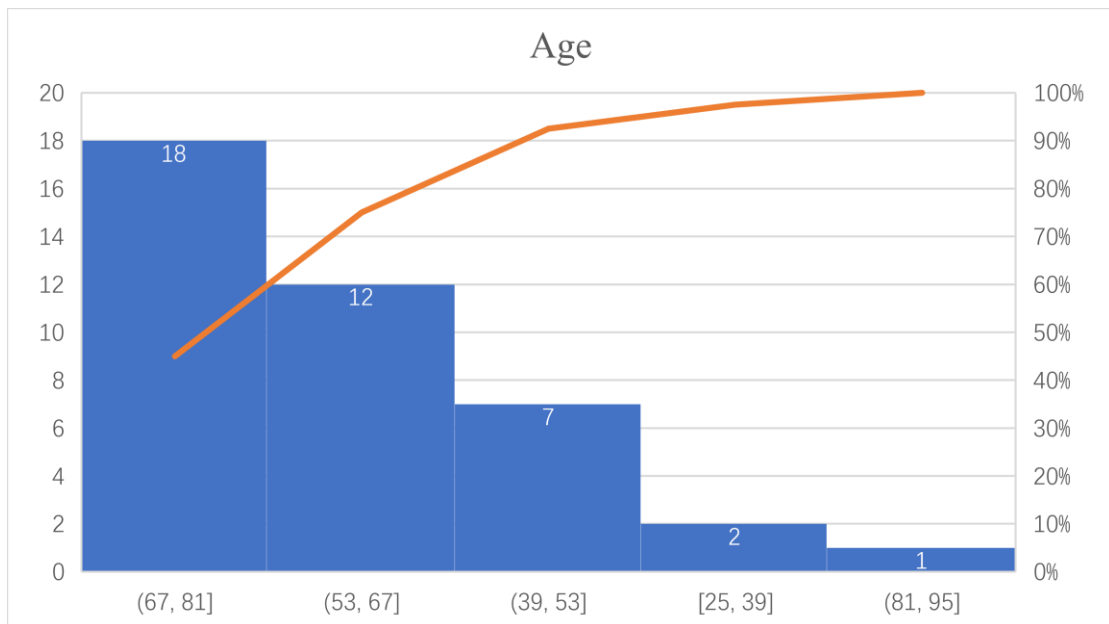


Figure 5 Age distribution of 40 patients

Figure 6 shows the gender situation of all 40 patients (21 male and 19 females).

Figure 7 shows the positive rate of male and female. Female has a 63% positive rate which is higher than male's positive rate of 52%.

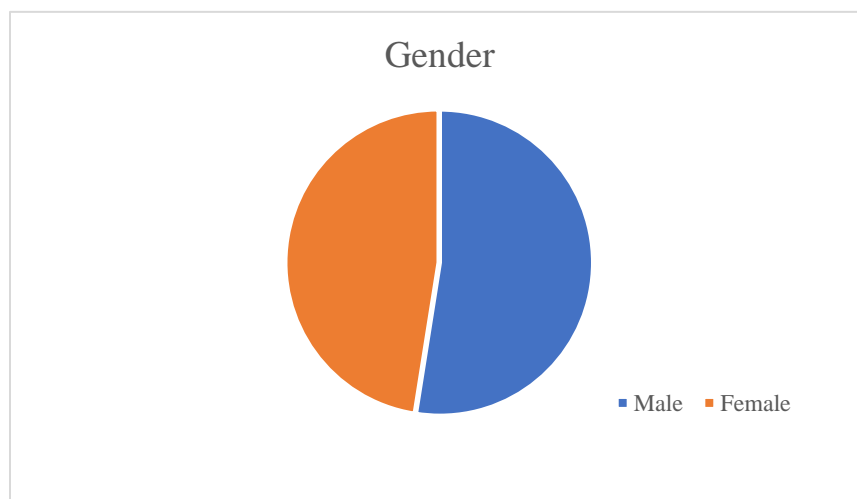


Figure 6 Gender of all patients

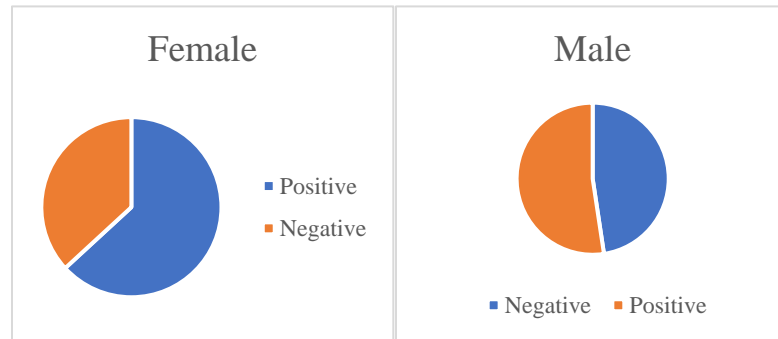


Figure 7 Medical examination results of male and female

#### 4.2 Machine Learning Results

The prediction model uses three algorithms, which include decision tree, naive Bayes, and logistic regression. The results after cross-validation can significantly improve accuracy. Cross-validation proposes one sample in turn among 40 samples and processed by machine learning algorithms. Finally, the best combination of the remaining 11 samples is obtained which has the highest accuracy.

Table 2 shows the results of three algorithms after cross validation.

Table 2 Cross-validation accuracy results

Algorithms	Average Training Result
Decision Tree	81.9%
Logistics Regression	89.8%
Naïve Bayes	75.1%

Given that there are only 40 data points, leave one out cross validation was used.

The Naive Bayes Classifier performs poorly due to the need for a large dataset to calculate the posterior probability of 52 factors among all patients with BPPV. With a small dataset, the probability is not accurate. The Decision Tree requires a large dataset to obtain the highest information gain to construct an optimal tree, resulting in limited classification ability when the dataset is small. Logistic Regression, however, does not require a large dataset to calculate the posterior probability. With 40 data points, the coefficients evolve 40 times, reflecting the significance of each factor, leading to its superior performance among the three models.

### **4.3 Discussion**

The dataset comprises 40 patients' survey answers. Upon analysis of 50 questions from the 40 patients, it was determined that the machine learning model may be overfitting. Using part of the patient information as a test set results in limited data available for model training, leading to potentially inaccurate results.

The patient background information in the survey primarily encompasses medical history, age, and gender. For BPPV, height, weight, and preferred sports are also relevant information. As discussed in Section 2.2, changes in head position can induce symptoms related to BPPV, such as vertigo. For instance, lifting weights results in vertical head movement, while playing basketball involves intense body movement that leads to head movement in various directions, mostly horizontal. Thus, it is advisable to gather more

patient background information.

In machine learning, factors such as age and gender are not deemed as significant characteristics due to their limited impact among the 50 other questions. The small dataset of 12 individuals, representing diverse ages and genders, may not reflect the independence of age and gender, contributing to low accuracy. However, dividing the sample into two parts by gender is not likely to improve accuracy significantly.



## Chapter 5 Conclusion and Future Work

This thesis presents a machine learning approach for BPPV classification through a patient survey data collection. A key contribution of this study is the improvement of the patient survey questionnaire and addressing its limitations, as well as offering suggestions for future BPPV prediction models. The revised survey, through the elimination of redundant questions and the addition of a section on patients' symptoms, resulted in a significant improvement in classification accuracy compared to prior research (70-74%) [4]. Among the three machine learning algorithms tested, logistic regression achieved the highest accuracy rate of 89.8%.

The recent enhancements to the survey, which included elimination of redundant questions and inclusion of a new section on patient symptoms, resulted in a significant improvement in accuracy. However, there is a large variability across cross-validation folds. This can be attributed to a small sample size, the absence of background questions, and high inter-question correlation, which will be discussed in more detail in the next sections.

Next, we suggest future work that may improve the classification results. The patient survey encompasses 50 questions and considers the patient's age and gender as two of the 52 factors, along with the results of medical tests, to be used as features in the machine learning model. However, not all 52 factors hold equal importance. Questions from the first and second sections of the survey ask about the patient's symptoms, with

the first section based on the patient's own description and the second section based on the medical definition of symptoms. Self-reported symptoms may not be as significant as symptoms assessed with medical definitions. For instance, in the machine learning process, age is treated as just another column alongside the results of the fifty questions. But in medical literature, individuals over 45 years old are more likely to develop BPPV [11]. Increasing the weight of age during the machine learning model training may enhance prediction accuracy.

It is recommended to include patients without dizziness symptoms in the patient population. Currently, the data collected pertains only to patients with ear or head related issues. Including healthy patients in the sample would provide a better characterization of the healthy population by the machine learning model and provide more data for researchers.

As previously noted in section 4.3 the limited patient background information of only medical history, age, and gender may not be sufficient. Including additional factors such as height, weight, and preferred sports activities could enhance the accuracy of the model.

## Bibliography

- [1] Qian SX, Li F, Zhuang JH, Chen Y, Yang HL, Zhou XW, Gu HH, Gao B. [Misdiagnosis and associated costs of benign paroxysmal positional vertigo]. *Zhonghua Yi Xue Za Zhi*. 2017 Apr 11;97(14):1057-1060. Chinese. doi: 10.3760/cma.j.issn.0376-2491.2017.14.006. PMID: 28395428.
- [2] Jin Z, Zhuang JH, Zhao ZX, Chen Y, Li YC. [Analysis of misdiagnosed cases with benign paroxysmal positional vertigo]. *Zhonghua Yi Xue Za Zhi*. 2012 May 22;92(19):1346-8. Chinese. PMID: 22883126.
- [3] Audigyblog, "Facts about dizziness: Vertigo: The Hearing and Balance Clinic: Denison," *The Hearing and Balance Clinic*, 22-Oct-2019. [Online]. Available: <https://www.thehearingclinic.org/services/facts-about-dizziness/>. [Accessed: 25-Jul-2022].
- [4] "Benign paroxysmal positional vertigo predictive diagnosis from patient ..." [Online]. Available: [https://epublications.marquette.edu/cgi/viewcontent.cgi?article=1640&context=theses\\_open](https://epublications.marquette.edu/cgi/viewcontent.cgi?article=1640&context=theses_open). [Accessed: 28-Jul-2022].
- [5] von Brevern M, Radtke A, Lezius F, Feldmann M, Ziese T, Lempert T, Neuhauser H. Epidemiology of benign paroxysmal positional vertigo: a population based study. *J Neurol Neurosurg Psychiatry*. 2007 Jul;78(7):710-5. doi: 10.1136/jnnp.2006.100420. Epub 2006 Nov 29. PMID: 17135456; PMCID: PMC2117684.
- [6] "Benign paroxysmal positional vertigo (BPPV)," *Johns Hopkins Medicine*, 13-Dec-2021. [Online]. Available: <https://www.hopkinsmedicine.org/health/conditions-and-diseases/benign-paroxysmal-positional-vertigo-bppv>. [Accessed: 25-Jul-2022].
- [7] S. Habbachi, W. Turki and M. Sayadi, "Study of the correlation between pupil position and diameter in video-nystagmography for nystagmus analysis,"

- International Image Processing, Applications and Systems Conference, 2014, pp. 1-4, doi: 10.1109/IPAS.2014.7043279.
- [8] P. Volf, J. Hejda, P. Kutilek, J. Hozman, J. Hozman and R. Černý, "Application of ellipsoid parameters for evaluation of nystagmus evoked during rotational chair test," 2020 43rd International Conference on Telecommunications and Signal Processing (TSP), 2020, pp. 153-157, doi: 10.1109/TSP49548.2020.9163569.
- [9] "Audiometry Test, hearing test," *Audiometry Test, Hearing Test | Mayfield Brain & Spine*. [Online]. Available: <https://mayfieldclinic.com/pe-hearing.htm>. [Accessed: 25-Jul-2022].
- [10] "NCI Dictionary of Cancer terms," *National Cancer Institute*. [Online]. Available: <https://www.cancer.gov/publications/dictionaries/cancer-terms/def/imaging-test>. [Accessed: 25-Jul-2022].
- [11] L. M. H. & Balance, "What to expect during a Balance Test," *LeMay Hearing Balance*, 15-Jun-2021. [Online]. Available: <https://hearingaidreno.com/what-to-expect-during-a-balance-test/>. [Accessed: 25-Jul-2022].
- [12] Auramo, Y., Juhola, M., & Pyykkö, I. (1993). An expert system for the computer-aided diagnosis of dizziness and vertigo. *Medical informatics = Medecine et informatique*, 18(4), 293–305. <https://doi.org/10.3109/14639239309025318>
- [13] Mira, E., Buizza, A., Magenes, G., Manfrin, M., & Schmid, R. (1990). Expert systems as a diagnostic aid in otoneurology. *ORL; journal for oto-rhino-laryngology and its related specialties*, 52(2), 96–103. <https://doi.org/10.1159/000276113>
- [14] E. Kentala, I. Pyykkö, Y. Auramo, J. Laurikkala, M. Juhola (1999) Otoneurological Expert System for Vertigo, *Acta Oto-Laryngologica*, 119:5, 517-521, DOI: [10.1080/00016489950180720](https://doi.org/10.1080/00016489950180720)
- [15] Bansal M. (2019). Development of an Experimental System "Computer-Aided Diagnosis in Neurotology (CADINO)" for Vertigo. *Indian journal of otolaryngology and head and neck surgery : official publication of the Association of Otolaryngologists*

- of India*, 71(3), 346–351. <https://doi.org/10.1007/s12070-019-01617-x>
- [16] Bankowitz, R. A., McNeil, M. A., Challinor, S. M., Parker, R. C., Kapoor, W. N., & Miller, R. A. (1989). A computer-assisted medical diagnostic consultation service. Implementation and prospective evaluation of a prototype. *Annals of internal medicine*, 110(10), 824–832. <https://doi.org/10.7326/0003-4819-110-10-824>
- [17] Yu, F., Wu, P., Deng, H., Wu, J., Sun, S., Yu, H., Yang, J., Luo, X., He, J., Ma, X., Wen, J., Qiu, D., Nie, G., Liu, R., Hu, G., Chen, T., Zhang, C., & Li, H. (2022). A Questionnaire-Based Ensemble Learning Model to Predict the Diagnosis of Vertigo: Model Development and Validation Study. *Journal of medical Internet research*, 24(8), e34126. <https://doi.org/10.2196/34126>
- [18] Feil, K., Feuerecker, R., Goldschagg, N., Strobl, R., Brandt, T., von Müller, A., Grill, E., & Strupp, M. (2018). Predictive Capability of an iPad-Based Medical Device (medx) for the Diagnosis of Vertigo and Dizziness. *Frontiers in neurology*, 9, 29. <https://doi.org/10.3389/fneur.2018.00029>
- [19] L. Masankaran, W. Viyanon and V. Mahasittiwat, "Classification of Benign Paroxysmal Positioning Vertigo Types from Dizziness Handicap Inventory using Machine Learning Techniques," 2018 International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS), 2018, pp. 209-214, doi: 10.1109/ICIIBMS.2018.8550002.
- [20] Richburg, Heidi; Povinelli, Richard J.; and Friedland, David, "Direct-to-Patient Survey for Diagnosis of Benign Paroxysmal Positional Vertigo" (2019). *Electrical and Computer Engineering Faculty Research and Publications*. 514. [https://epublications.marquette.edu/electric\\_fac/514](https://epublications.marquette.edu/electric_fac/514)
- [21] *Benign paroxysmal positional vertigo (BPPV)*. VeDA. (2022, May 31). Retrieved July 25, 2022, from <https://vestibular.org/article/diagnosis-treatment/types-of-vestibular-disorders/benign-paroxysmal-positional-vertigo-bppv/>

- [22] J. Brownlee, "How to choose a feature selection method for machine learning," *Machine Learning Mastery*, 20-Aug-2020. [Online]. Available: <https://machinelearningmastery.com/feature-selection-with-real-and-categorical-data/>. [Accessed: 25-Jul-2022].
- [23] "What is logistic regression?," *IBM*. [Online]. Available: <https://www.ibm.com/topics/logistic-regression>. [Accessed: 25-Jul-2022].
- [24] "Bayesian analysis," *Encyclopædia Britannica*. [Online]. Available: <https://www.britannica.com/science/Bayesian-analysis>. [Accessed: 25-Jul-2022].
- [25] "Naive Bayes classifiers," *GeeksforGeeks*, 02-Feb-2022. [Online]. Available: <https://www.geeksforgeeks.org/naive-bayes-classifiers/>. [Accessed: 25-Jul-2022].
- [26] "Sklearn.tree.decisiontreeclassifier," *scikit*. [Online]. Available: <https://scikit-learn.org/stable/modules/generated/sklearn.tree.DecisionTreeClassifier.html>. [Accessed: 25-Jul-2022].
- [27] Friedland, D. R., Tarima, S., Erbe, C., & Miles, A. (2016). Development of a Statistical Model for the Prediction of Common Vestibular Diagnoses. *JAMA otolaryngology-- head & neck surgery*, 142(4), 351–356. <https://doi.org/10.1001/jamaoto.2015.3663>
- [28] M. Siermala, M. Juhola, J. Laurikkala, K. Iltanen, E. Kentala and I. Pyykko, "Evaluation and classification of otoneurological data with new data analysis methods based on machine learning", *Information Sciences*, vol. 177, pp. 1963-1976, 2007.

## **Appendix A**

The appendix shows screenshots of every page in the patient's survey. The first step is creating a new database for recording new patient's answer and generating a Patent Record ID for the patient in the database (Figure 9). Figure 10 is the instruction page of the survey. It tells the number of questions.

Figure 8 shows the home page of the survey.

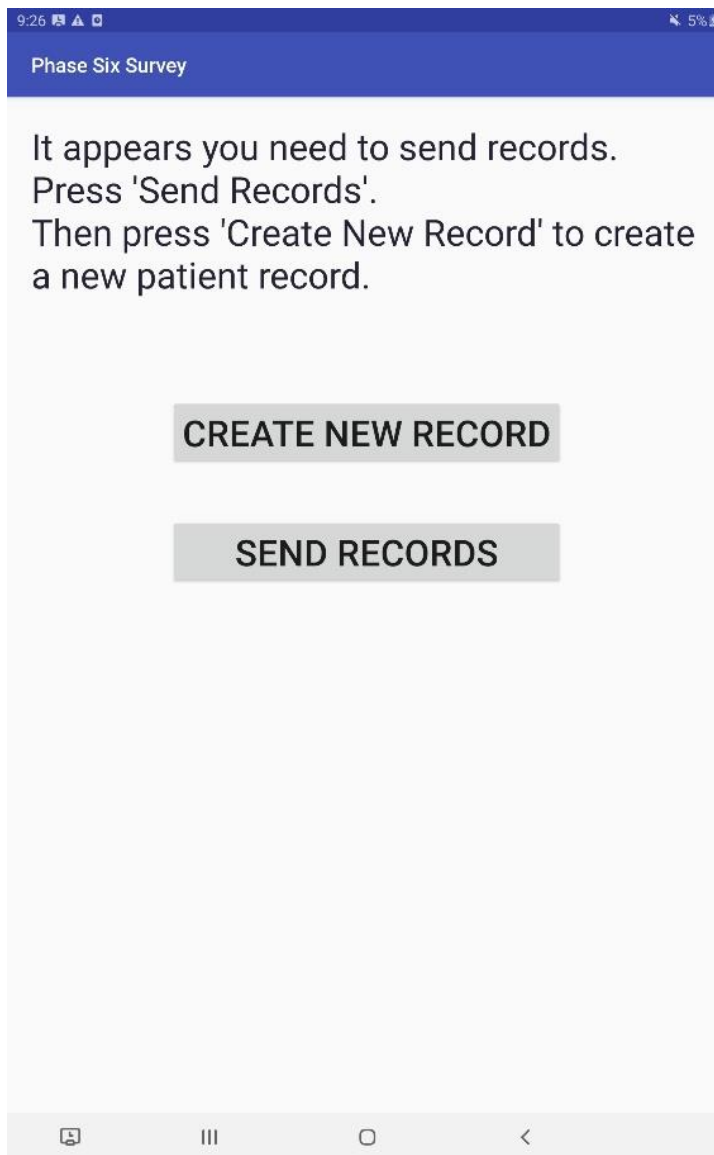


Figure 8 Home page



Figure 9 shows the welcome page of the survey, and a patient record ID is generated at the back.

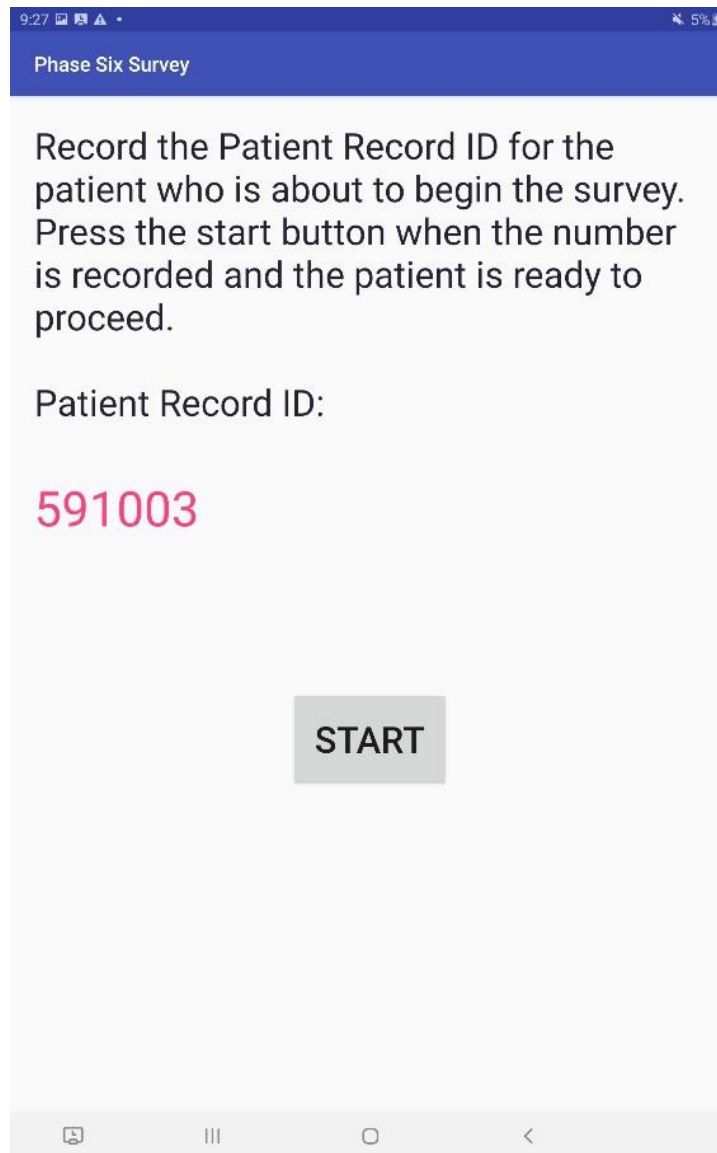


Figure 9 The welcome page and generate patient ID.

Figure 10 is the instruction page of the survey. It tells the number of questions.

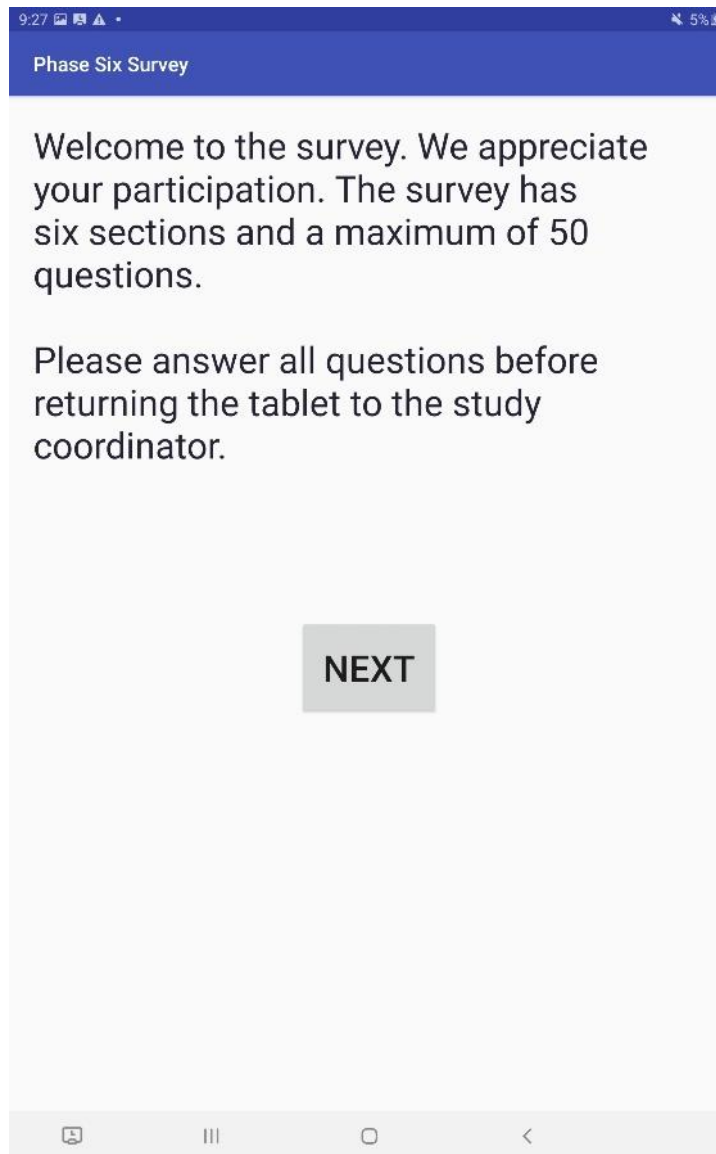


Figure 10 Summary of the survey and summary of the first section

Figure 11 is the instruction page of the first section. The number of questions is shown. Figure 8-12 are the questions in the first section, which provide scenarios of common symptoms for patients to choose.



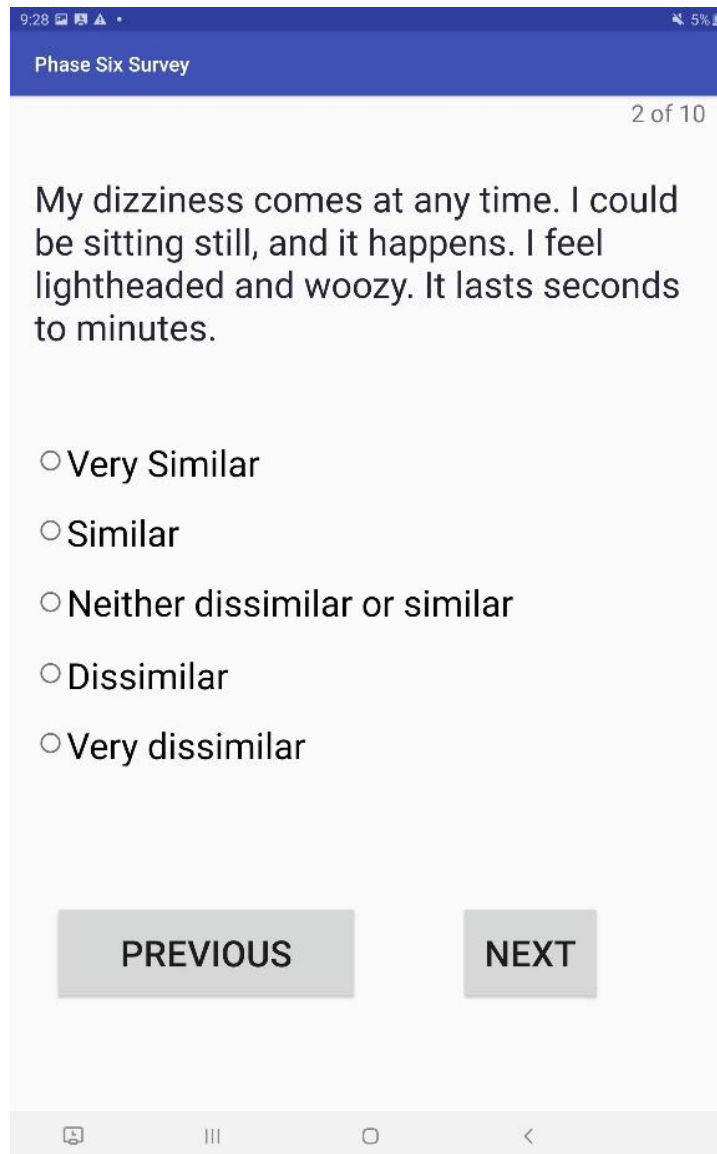
Figure 11 Instruction page of the first section

Figure 12 shows the first question in the first section.

The screenshot shows a mobile application interface for a survey. At the top, a blue header bar contains the text "Phase Six Survey" and "1 of 10". Below the header, the question text reads: "My dizziness often comes when lying down or turning in bed. It feels like I am spinning or moving. The dizziness lasts less than a minute. This has happened on many days or weeks." Below the question, there are five radio button options: "Very Similar", "Similar", "Neither dissimilar or similar", "Dissimilar", and "Very dissimilar". At the bottom of the question area, there are two buttons: "PREVIOUS" and "NEXT". The bottom of the screen shows a standard Android navigation bar with icons for home, back, and other functions.

Figure 12 First question in the first section

Figure 13 is the second question in the first section.



9:28 5% 2 of 10

Phase Six Survey

2 of 10

My dizziness comes at any time. I could be sitting still, and it happens. I feel lightheaded and woozy. It lasts seconds to minutes.

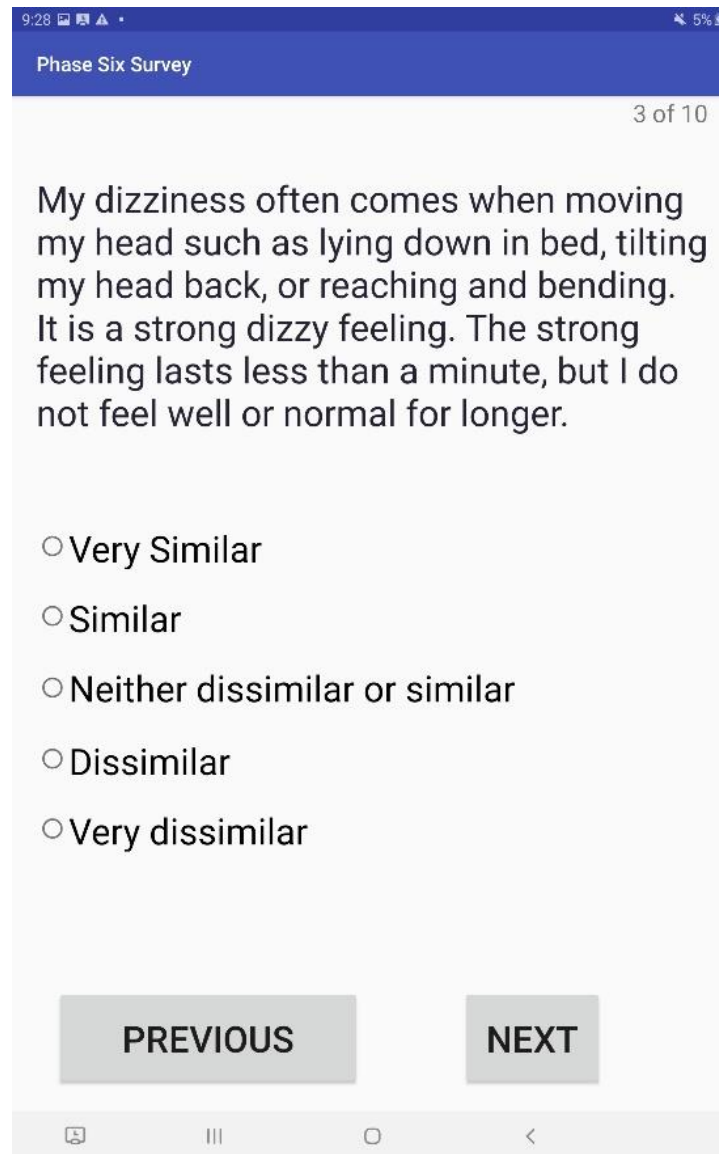
- Very Similar
- Similar
- Neither dissimilar or similar
- Dissimilar
- Very dissimilar

PREVIOUS NEXT

III O <

Figure 13 Second question in the first section

Figure 14 is the third question in the first section.



9:28 5%  
Phase Six Survey  
3 of 10

My dizziness often comes when moving my head such as lying down in bed, tilting my head back, or reaching and bending. It is a strong dizzy feeling. The strong feeling lasts less than a minute, but I do not feel well or normal for longer.

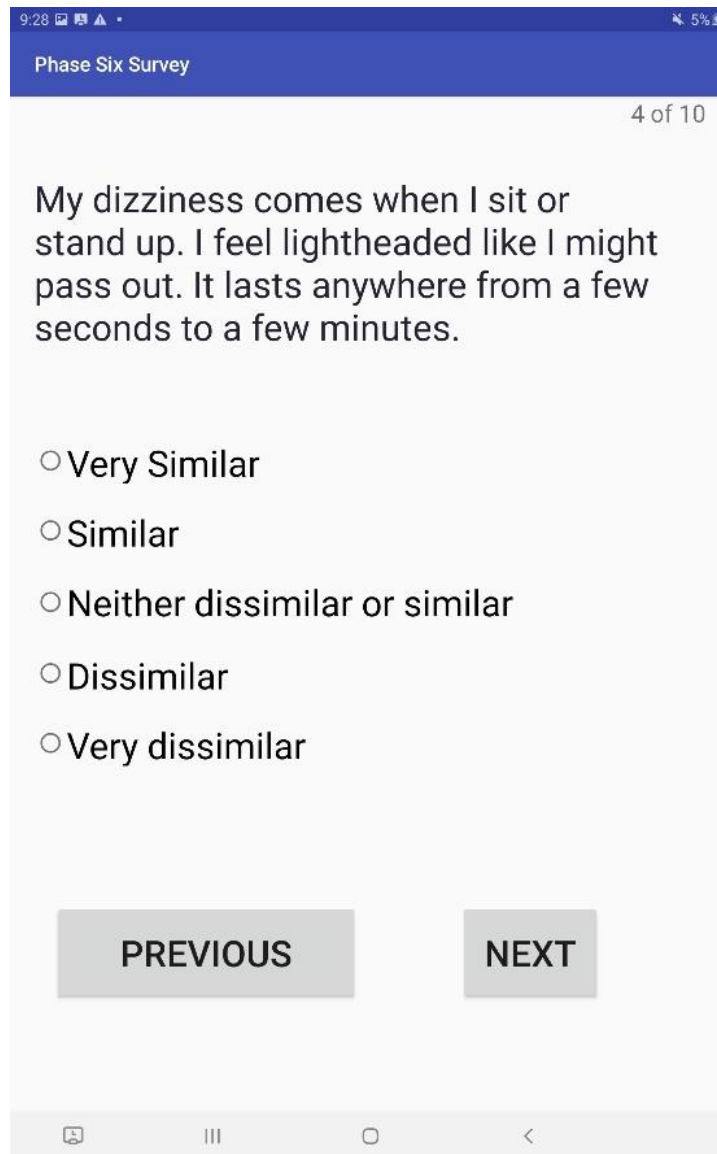
- Very Similar
- Similar
- Neither dissimilar or similar
- Dissimilar
- Very dissimilar

PREVIOUS NEXT

III O <

Figure 14 Third question in the first section

Figure 15 is the 4<sup>th</sup> question in the first section.



9:28 5% 4 of 10

Phase Six Survey

4 of 10

My dizziness comes when I sit or stand up. I feel lightheaded like I might pass out. It lasts anywhere from a few seconds to a few minutes.

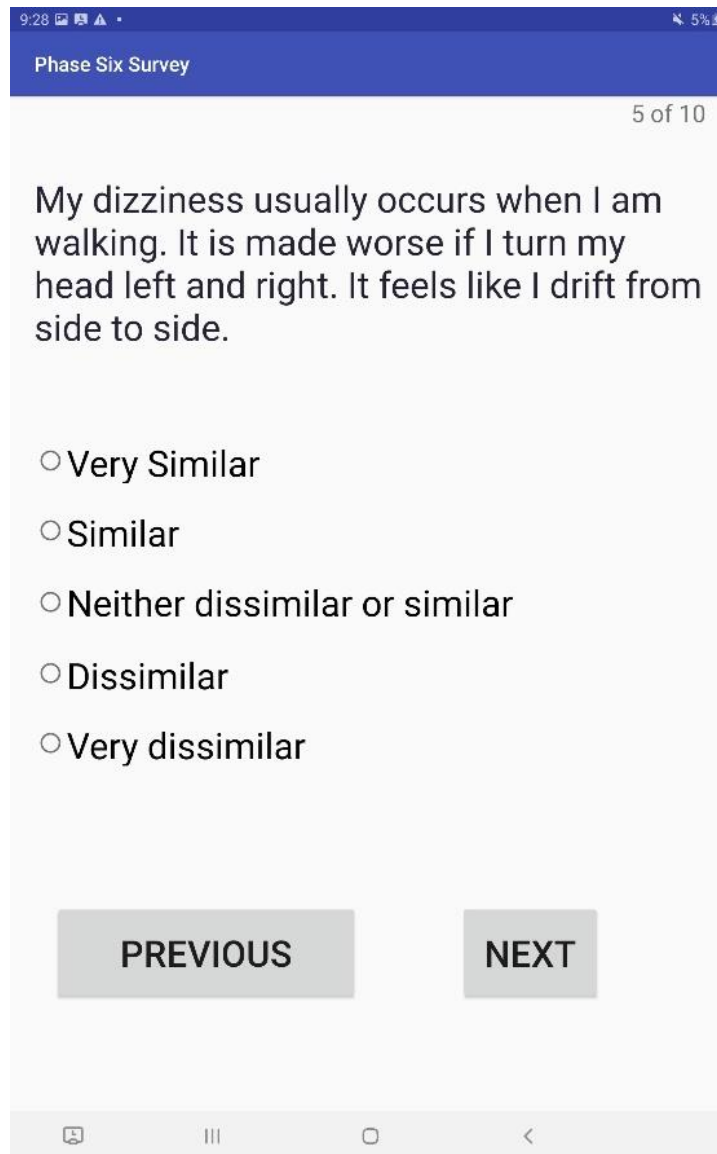
- Very Similar
- Similar
- Neither dissimilar or similar
- Dissimilar
- Very dissimilar

PREVIOUS NEXT

III O <

Figure 15 4<sup>th</sup> question in first section

Figure 16 is the 5<sup>th</sup> question in the first section.



9:28 5% 5 of 10

Phase Six Survey

5 of 10

My dizziness usually occurs when I am walking. It is made worse if I turn my head left and right. It feels like I drift from side to side.

- Very Similar
- Similar
- Neither dissimilar or similar
- Dissimilar
- Very dissimilar

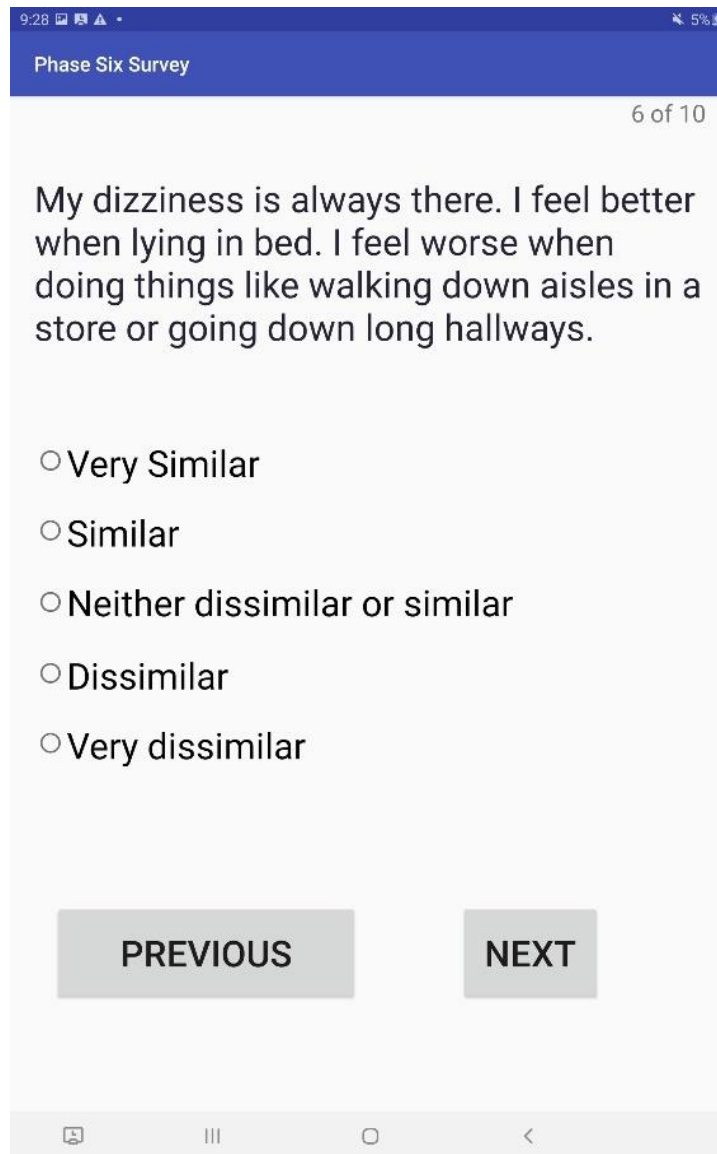
PREVIOUS NEXT

III <

Figure 16 5<sup>th</sup> questions in first section



Figure 17 is the 6<sup>th</sup> question in the first section.



9:28 5% 6 of 10

Phase Six Survey

6 of 10

My dizziness is always there. I feel better when lying in bed. I feel worse when doing things like walking down aisles in a store or going down long hallways.

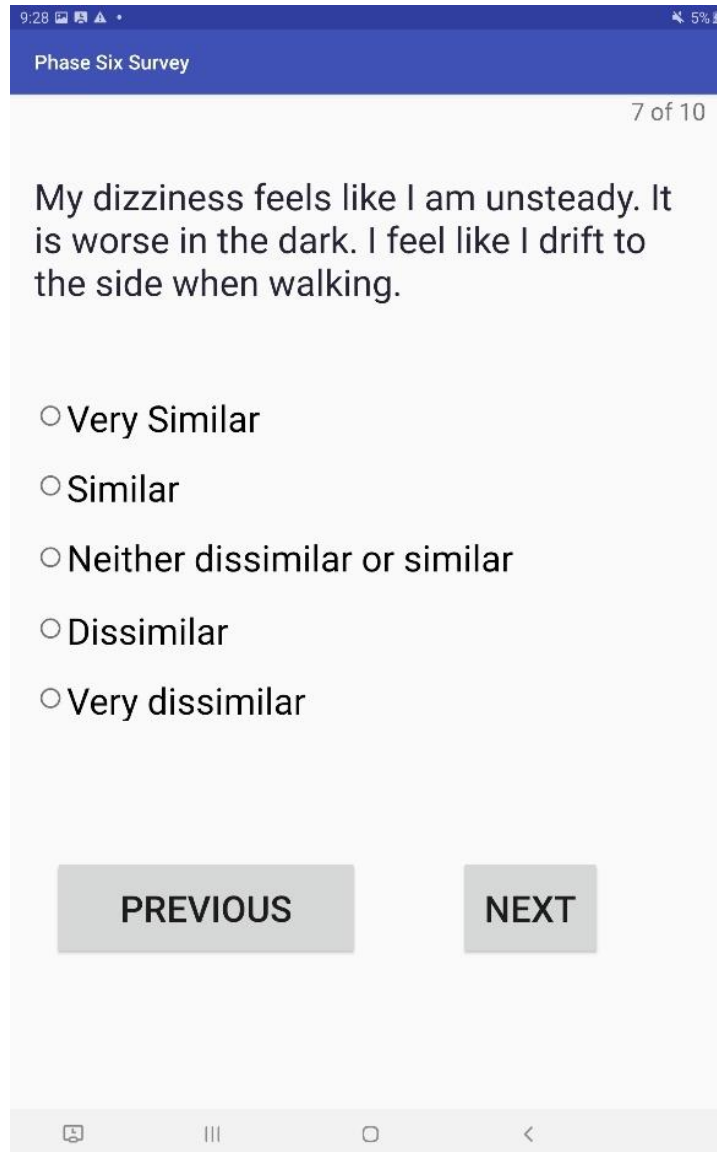
- Very Similar
- Similar
- Neither dissimilar or similar
- Dissimilar
- Very dissimilar

PREVIOUS NEXT

III O <

Figure 17 6<sup>th</sup> questions in first section

Figure 18 is the 7<sup>th</sup> question in the first section.



9:28 5% 7 of 10

Phase Six Survey

7 of 10

My dizziness feels like I am unsteady. It is worse in the dark. I feel like I drift to the side when walking.

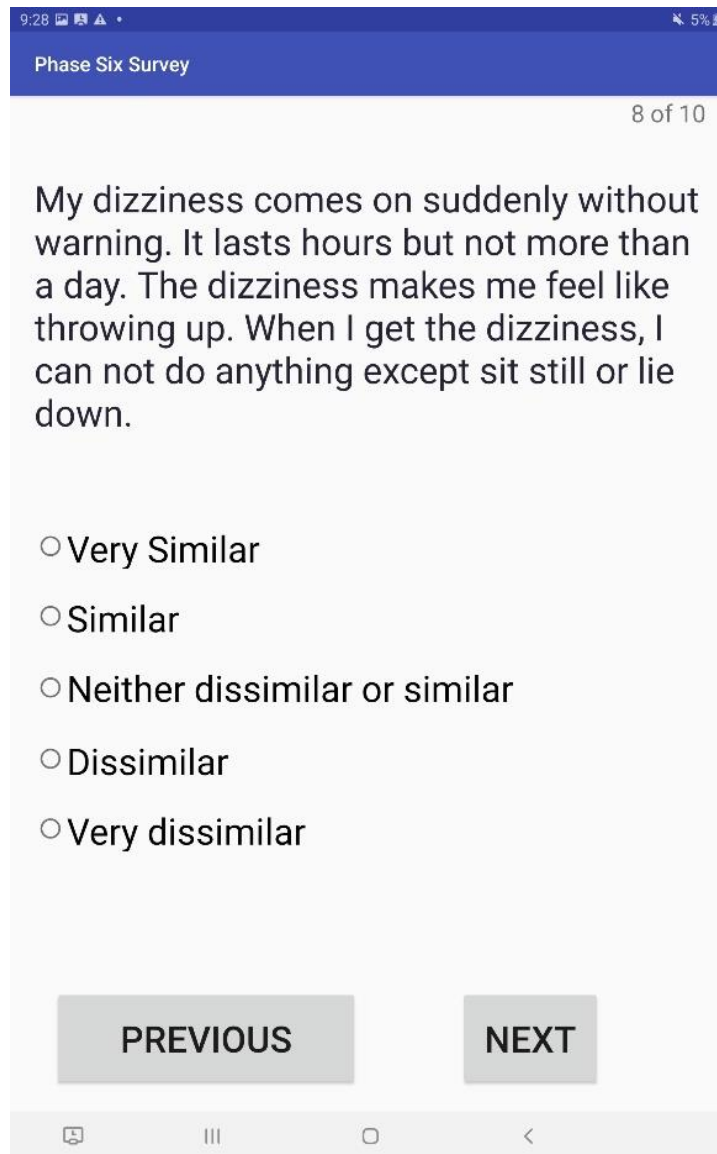
- Very Similar
- Similar
- Neither dissimilar or similar
- Dissimilar
- Very dissimilar

PREVIOUS NEXT

Navigation icons: back, home, search, forward

Figure 18 7<sup>th</sup> questions in first section

Figure 19 is the 8<sup>th</sup> question in the first section.



The image shows a mobile application interface for a survey. At the top, a blue header bar contains the text "Phase Six Survey" and "8 of 10". Below the header, the question text reads: "My dizziness comes on suddenly without warning. It lasts hours but not more than a day. The dizziness makes me feel like throwing up. When I get the dizziness, I can not do anything except sit still or lie down." Below the text are five radio button options: "Very Similar", "Similar", "Neither dissimilar or similar", "Dissimilar", and "Very dissimilar". At the bottom of the question area are two grey buttons labeled "PREVIOUS" and "NEXT". The bottom of the screen shows a standard Android navigation bar with icons for home, back, and other functions.

9:28 5%  
Phase Six Survey  
8 of 10

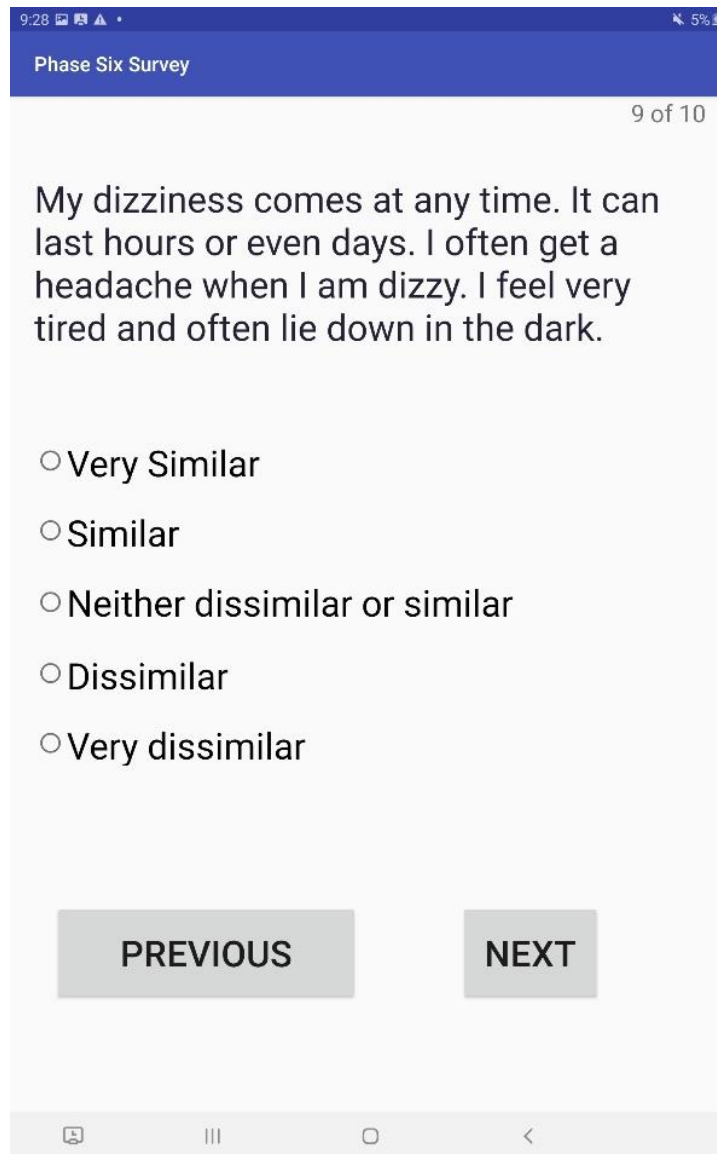
My dizziness comes on suddenly without warning. It lasts hours but not more than a day. The dizziness makes me feel like throwing up. When I get the dizziness, I can not do anything except sit still or lie down.

Very Similar  
 Similar  
 Neither dissimilar or similar  
 Dissimilar  
 Very dissimilar

PREVIOUS NEXT

Figure 19 8<sup>th</sup> questions in first section

Figure 20 is the 9<sup>th</sup> question in the first section.



9:28 5% 9 of 10

Phase Six Survey

9 of 10

My dizziness comes at any time. It can last hours or even days. I often get a headache when I am dizzy. I feel very tired and often lie down in the dark.

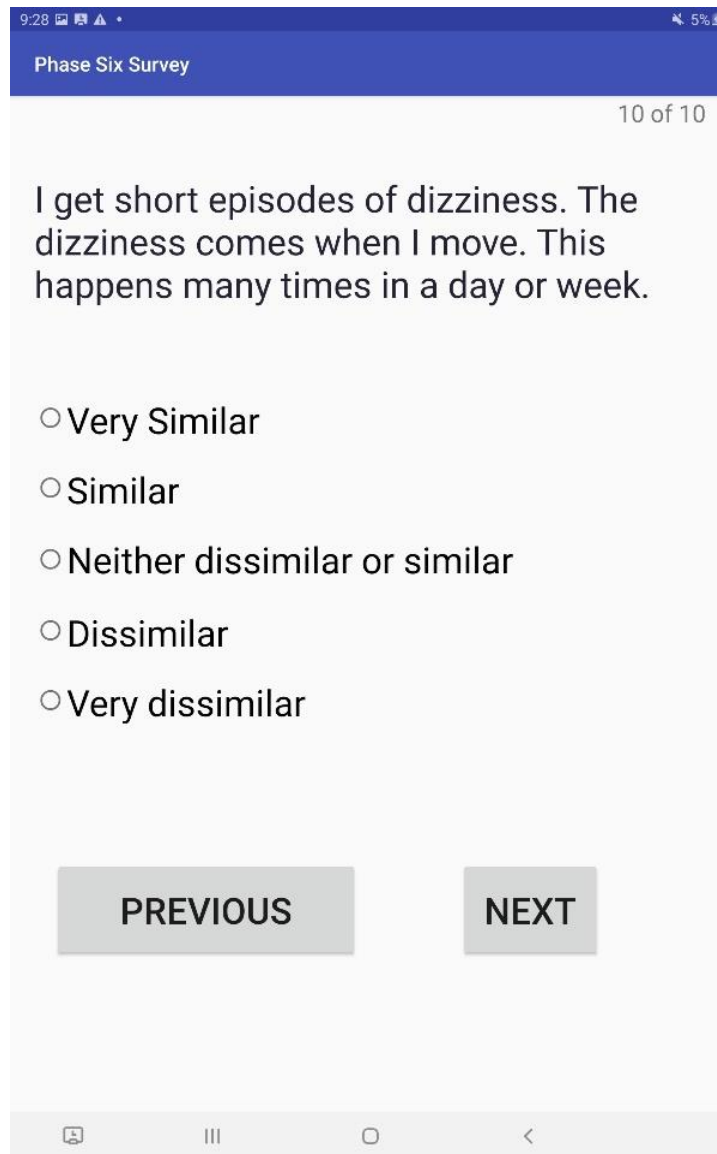
- Very Similar
- Similar
- Neither dissimilar or similar
- Dissimilar
- Very dissimilar

PREVIOUS NEXT

III O <

Figure 20 9<sup>th</sup> question in first section

Figure 21 is the 10<sup>th</sup> question in the first section.



The screenshot shows a mobile application interface for a survey. At the top, a blue header bar contains the text "Phase Six Survey" and "10 of 10". Below the header, the question text reads: "I get short episodes of dizziness. The dizziness comes when I move. This happens many times in a day or week." There are five radio button options listed below the question: "Very Similar", "Similar", "Neither dissimilar or similar", "Dissimilar", and "Very dissimilar". At the bottom of the question area, there are two grey buttons labeled "PREVIOUS" and "NEXT". The bottom of the screen shows a standard Android navigation bar with icons for home, back, and other functions.

Figure 21 10<sup>th</sup> question in first section

Figure 22 is the instruction page of the second section. As section 3.2.1 introduced, the section provides four medical definitions of different dizziness are shown in Figure 23. Figure 24-29 are the questions in this section. A summary of this section is generated for patients to review their answers, which shows in Figure 18.

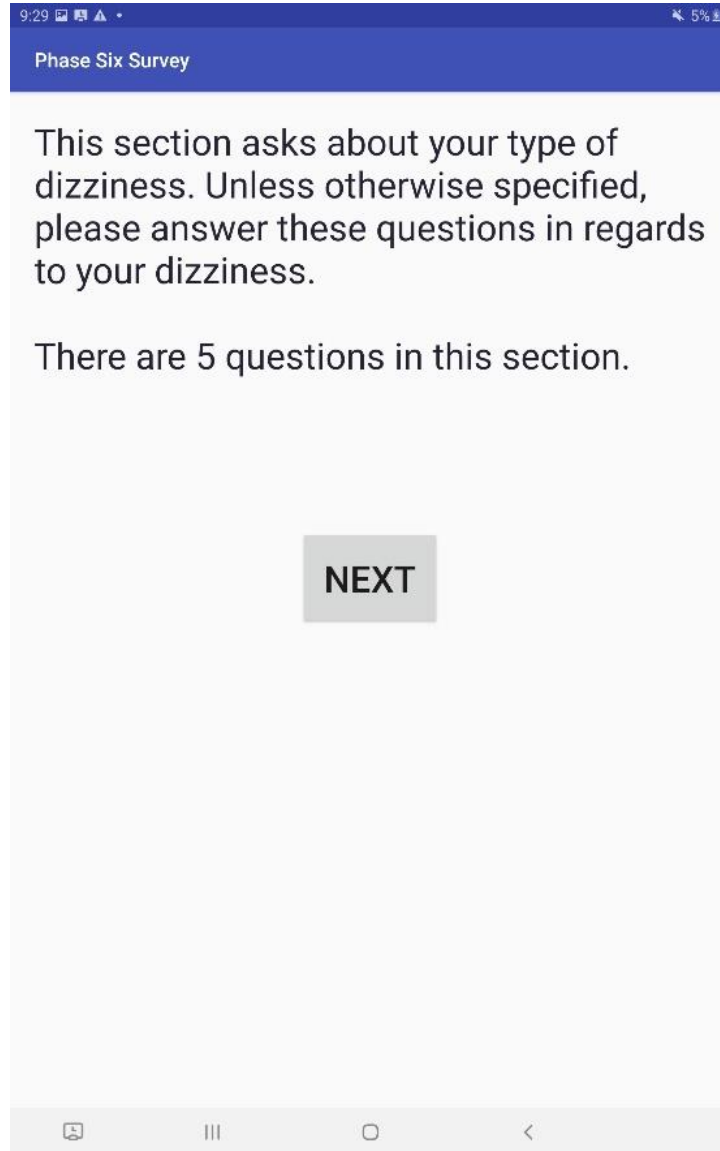


Figure 22 Summary of second section and definition of necessary medical terms

Four medical definitions of different dizziness are shown in Figure 23.

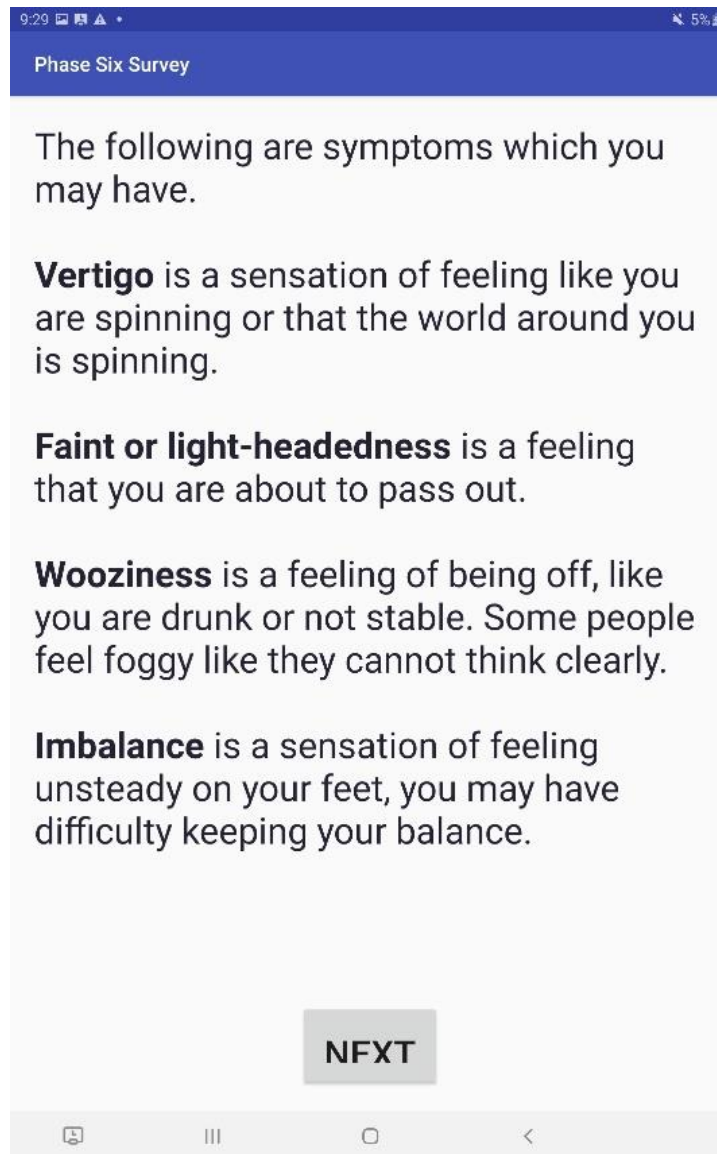
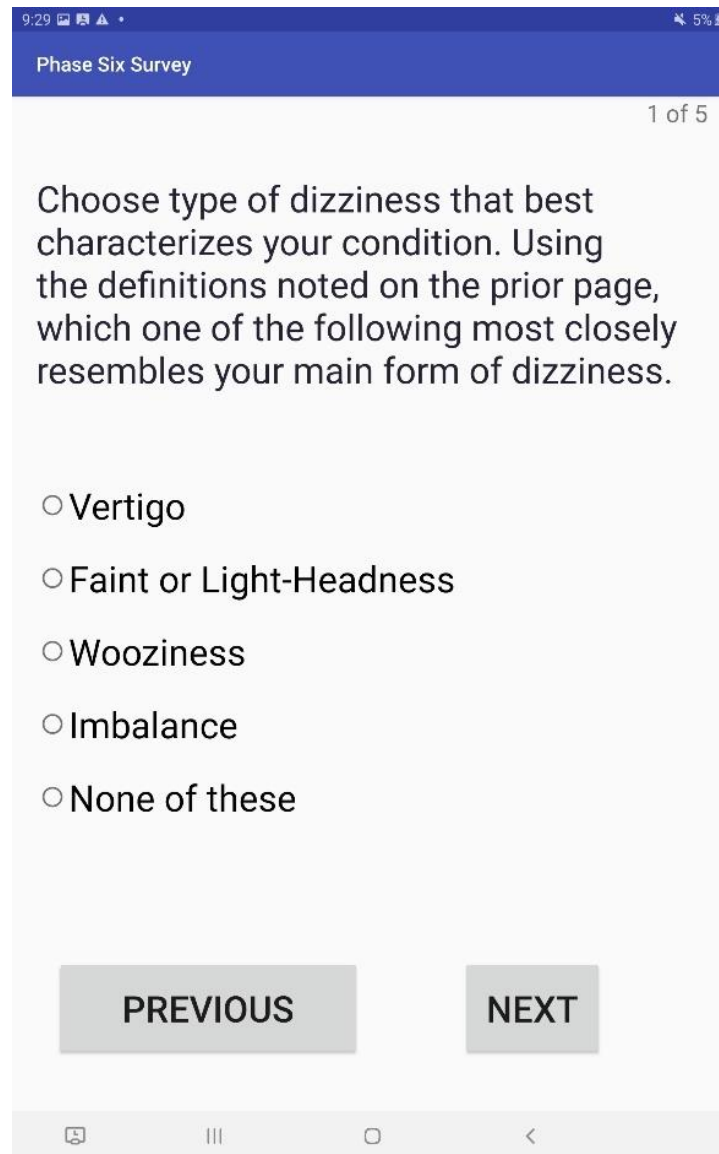


Figure 23 Definition of four dizziness

Figure 24 is the first question in the second section.



9:29 5%

Phase Six Survey

1 of 5

Choose type of dizziness that best characterizes your condition. Using the definitions noted on the prior page, which one of the following most closely resembles your main form of dizziness.

- Vertigo
- Faint or Light-Headness
- Wooziness
- Imbalance
- None of these

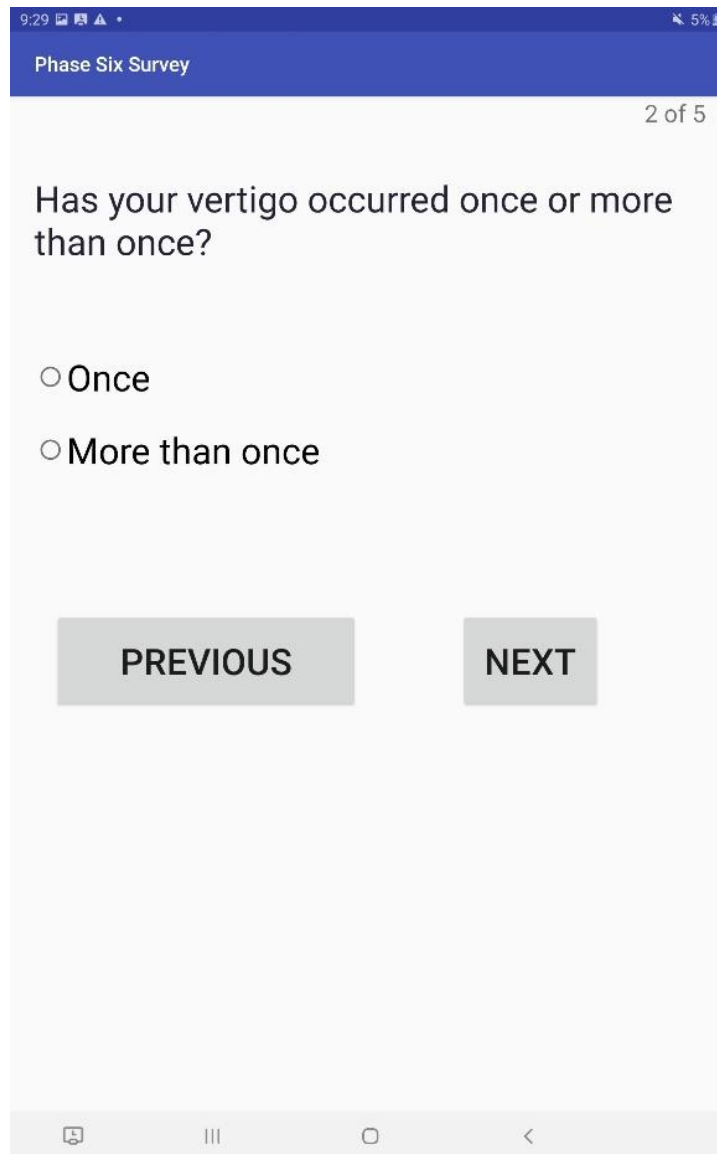
PREVIOUS NEXT

☰ ☐ <

Figure 24 First question in second section



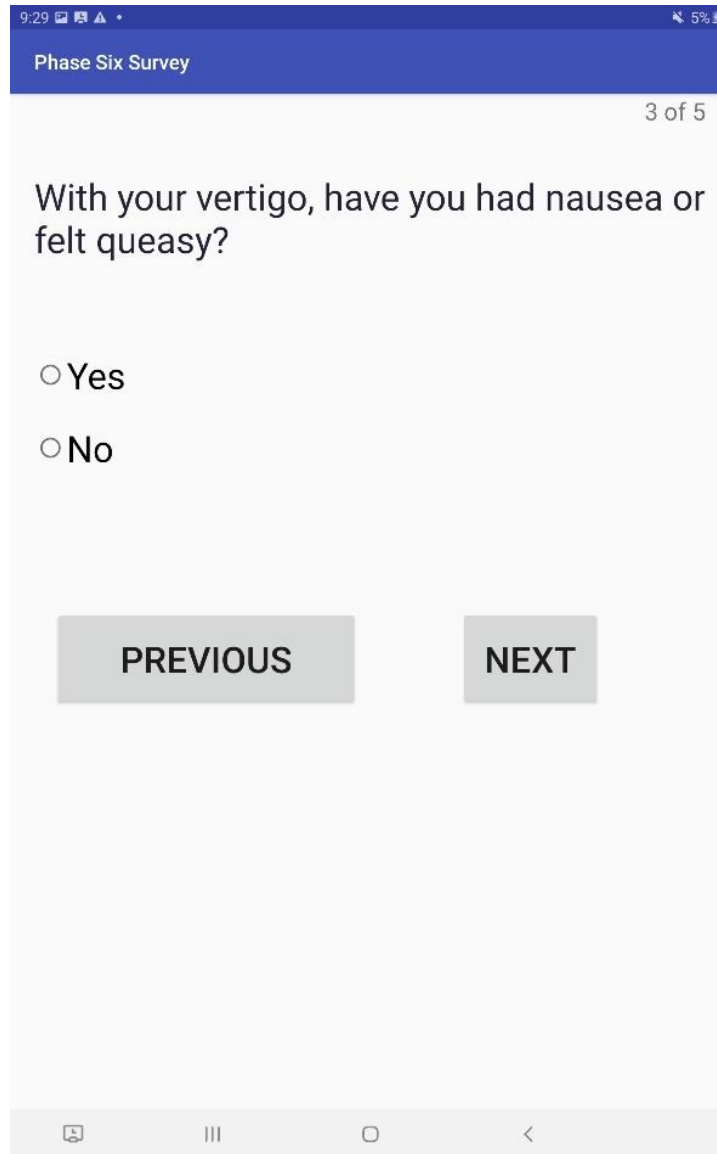
Figure 25 is the second question in the second section.



The image is a screenshot of a mobile application interface for a survey. At the top, there is a blue header bar with the text "Phase Six Survey" on the left and "2 of 5" on the right. Below the header, the question text reads "Has your vertigo occurred once or more than once?". There are two radio button options: "Once" and "More than once". At the bottom of the question area, there are two grey rectangular buttons labeled "PREVIOUS" and "NEXT". The bottom of the screen shows a standard Android navigation bar with icons for home, back, and other functions.

Figure 25 Second question in second section

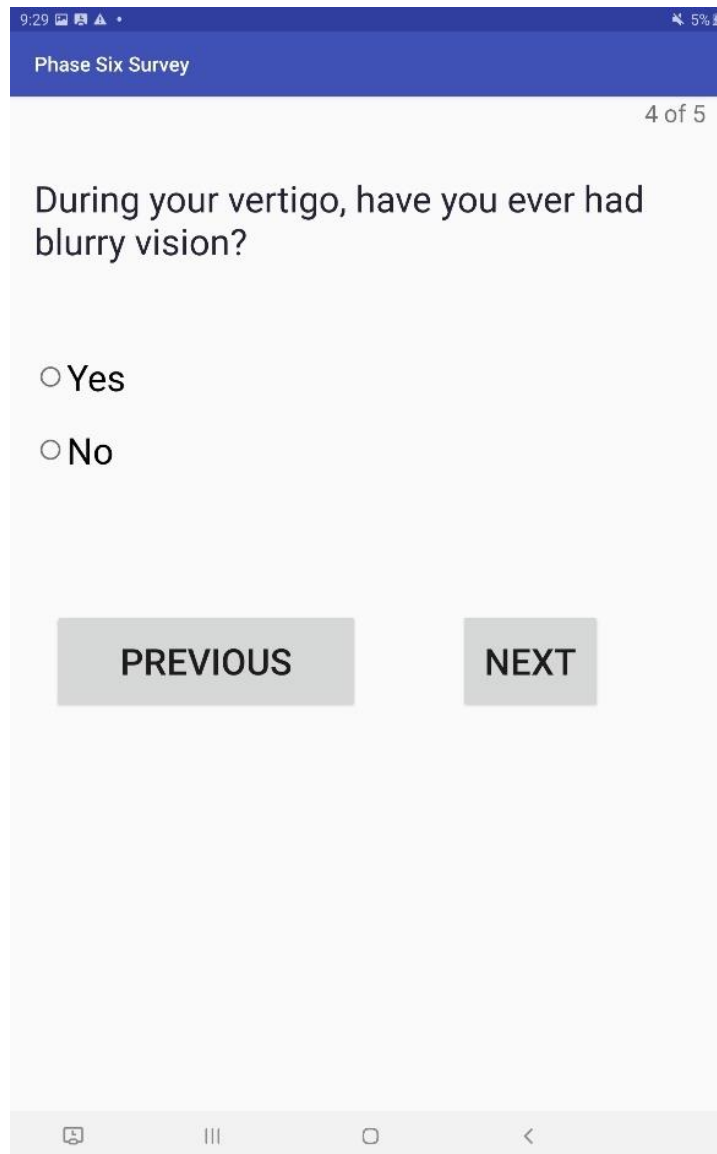
Figure 26 is the third question in the second section.



The image is a screenshot of a mobile application interface for a survey. At the top, there is a blue header bar with the text "Phase Six Survey" on the left and "3 of 5" on the right. Below the header, the question text reads "With your vertigo, have you had nausea or felt queasy?". There are two radio button options: "Yes" and "No". At the bottom of the question area, there are two grey rectangular buttons labeled "PREVIOUS" and "NEXT". The bottom of the screen shows a standard Android navigation bar with icons for back, home, and recent apps.

Figure 26 Third question in second section

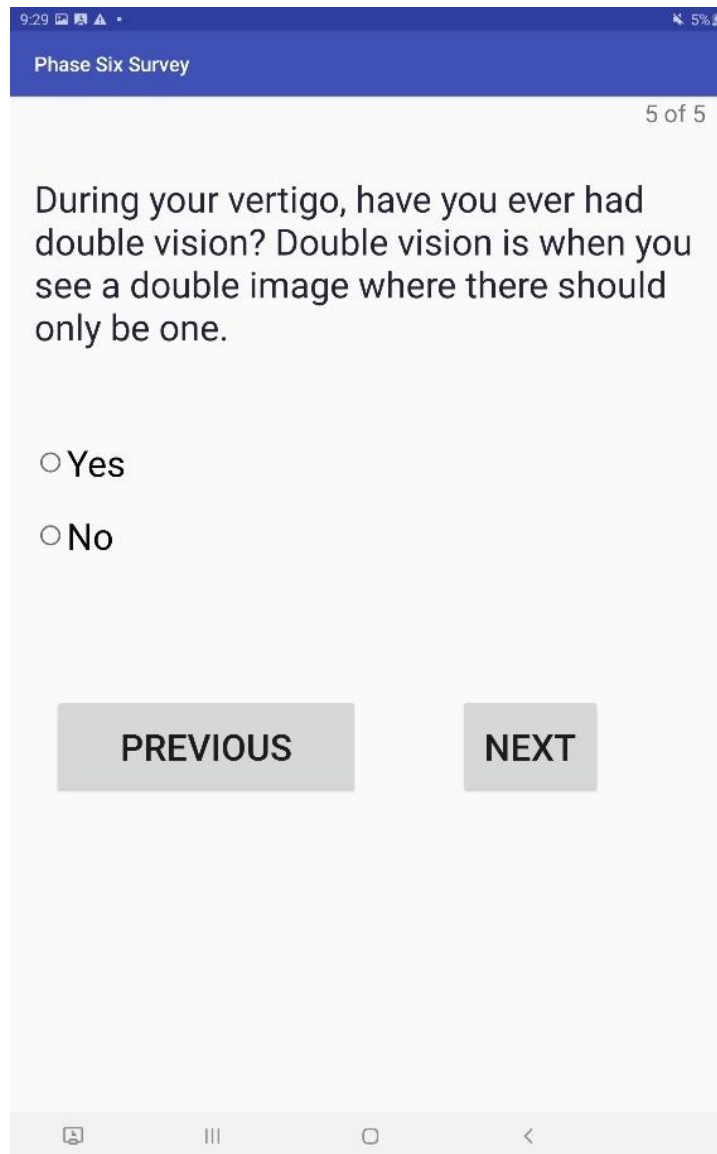
Figure 27 is the 4<sup>th</sup> question in the second section.



The screenshot shows a mobile application interface for a survey. At the top, a blue header bar contains the text "Phase Six Survey" and "4 of 5". Below the header, the question text reads: "During your vertigo, have you ever had blurry vision?". There are two radio button options: "Yes" and "No". At the bottom of the question area, there are two grey buttons labeled "PREVIOUS" and "NEXT". The bottom of the screen shows a standard Android navigation bar with icons for home, back, and other functions.

Figure 27 4<sup>th</sup> question in second section

Figure 28 is the last question in the second section.



9:29 5% 5 of 5

Phase Six Survey

5 of 5

During your vertigo, have you ever had double vision? Double vision is when you see a double image where there should only be one.

Yes

No

PREVIOUS NEXT

Android navigation bar icons: back, home, recent apps, and search.

Figure 28 5<sup>th</sup> question in second section

Figure 29 shows the summary page of the second section.

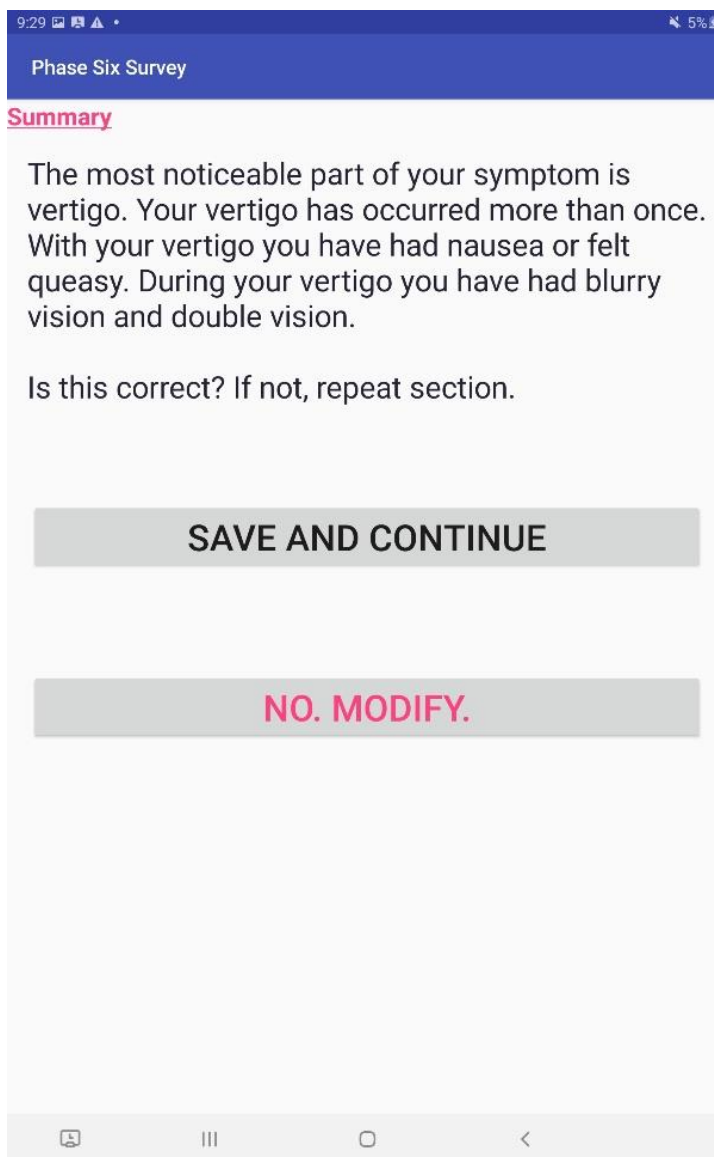


Figure 29 Summary of second section

The topic of the third section is duration and frequency of patients' symptoms, which is shown in Figure 30. Two example scenarios to eliminate misunderstandings shown in Figure 31 and 32. Figure 33-38 show questions in the third section ask about patients' duration and frequency. Figure 39 summarizes the answers in this section for patients to review.

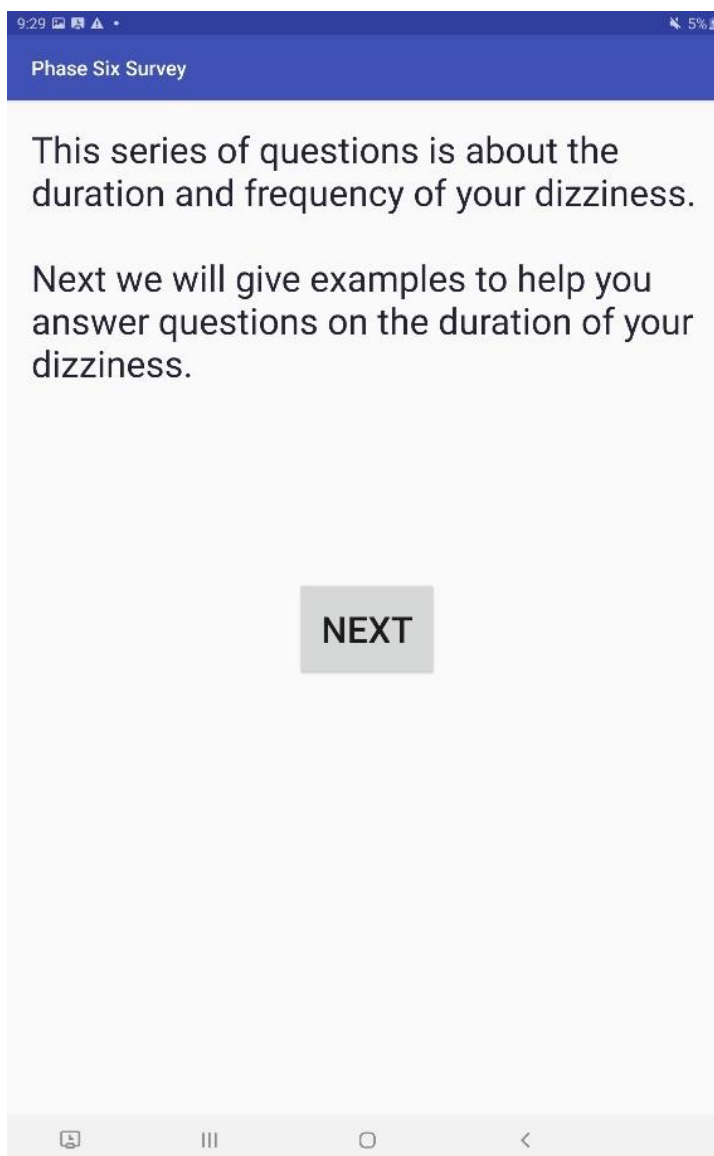


Figure 30 Introduction of third section

9:29 5%

Phase Six Survey

## Scenario 1

Example of how to answer questions based on the above scenario.

You turn over in bed and notice extreme dizziness that lasts for about 30 seconds. An hour later you turn in bed again and have the same thing.  
This represents two spells/episodes of dizziness lasting 30 seconds (NOT dizziness lasting an hour)

---

Did your dizziness last between seconds to a few minutes?

Yes  
 No

Did your dizziness last between 20 minutes and an hour?

Yes  
 No

PREVIOUS NEXT

Navigation icons: home, list, search, back

Figure 31 Scenario 1 of how to answer questions.

9:29 5%

Phase Six Survey

## Scenario 2

Example of how to answer questions based on the above scenario.

Almost every morning when you get out of bed you have severe dizziness lasting about a minute. This goes on every day for two weeks. This represents spells/episodes of dizziness lasting about a minute (NOT dizziness lasting 2 weeks)

Did your dizziness last between seconds to 1 minute?

Yes  
 No

Did your dizziness last more than a day?

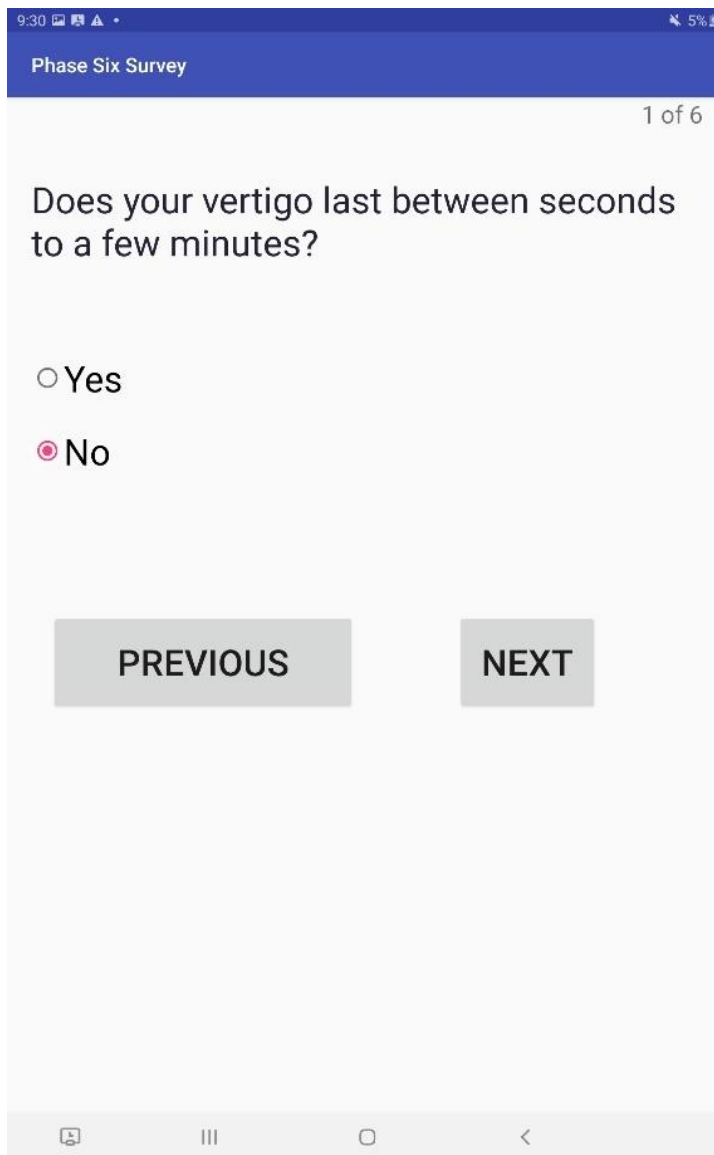
Yes  
 No

**PREVIOUS** **CONTINUE**

Navigation icons: back, home, search, forward

Figure 32 Scenario 2 of how to answer questions.





9:30 5%

Phase Six Survey

1 of 6

Does your vertigo last between seconds to a few minutes?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 33 First question of this section

9:30 5% 2 of 6

Phase Six Survey

2 of 6

Does your vertigo last between 20 minutes and an hour?

Yes

No

PREVIOUS NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile survey application. At the top, there is a blue header bar with the text 'Phase Six Survey'. Below the header, the status bar shows the time '9:30', battery level '5%', and '2 of 6' questions. The main content area is white and contains the question 'Does your vertigo last between 20 minutes and an hour?'. Below the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area, there are two grey buttons labeled 'PREVIOUS' and 'NEXT'. At the very bottom of the screen is a navigation bar with four icons: a back arrow, a home icon, a search icon, and a forward arrow.

Figure 34 Second question of this section

9:30 5%

Phase Six Survey

3 of 6

Does your vertigo last more than an hour but less than 12 hours?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile application interface for a survey. At the top, there is a blue header bar with the text 'Phase Six Survey'. Below the header, the status bar shows the time '9:30' and battery level '5%'. The main content area is white and contains the question 'Does your vertigo last more than an hour but less than 12 hours?'. Below the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area, there are two grey rectangular buttons labeled 'PREVIOUS' and 'NEXT'. The very bottom of the screen shows a standard Android navigation bar with icons for back, home, search, and forward.

Figure 35 Third question of this section

9:30 6% 6%

Phase Six Survey

4 of 6

Does your vertigo last more than 12 hours but not more than 1 day?

Yes

No

PREVIOUS NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile survey application. At the top, there is a blue header bar with the text 'Phase Six Survey'. Below the header, the status bar shows the time as 9:30 and battery level as 6%. The main content area is white and contains a question: 'Does your vertigo last more than 12 hours but not more than 1 day?'. Below the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area, there are two grey buttons labeled 'PREVIOUS' and 'NEXT'. The very bottom of the screen shows a standard Android navigation bar with icons for back, home, search, and forward.

Figure 36 4<sup>th</sup> question of this section

9:30 6% 6%

Phase Six Survey

5 of 6

Does your vertigo last more than a day?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile survey application. At the top, there is a blue header bar with the text "Phase Six Survey". Below the header, the status bar shows the time "9:30" and battery level "6%". The main content area is white and contains the question "Does your vertigo last more than a day?". Below the question are two radio button options: "Yes" and "No". At the bottom of the question area, there are two grey buttons labeled "PREVIOUS" and "NEXT". The very bottom of the screen shows a standard Android navigation bar with icons for back, home, search, and forward.

Figure 37 5<sup>th</sup> question of this section

9:31 6% 6 of 6

Phase Six Survey

6 of 6

Is your vertigo with you 24 hours a day, never stopping.

Yes

No

PREVIOUS NEXT

Navigation icons: back, home, search, forward

Figure 38 6<sup>th</sup> question of this section

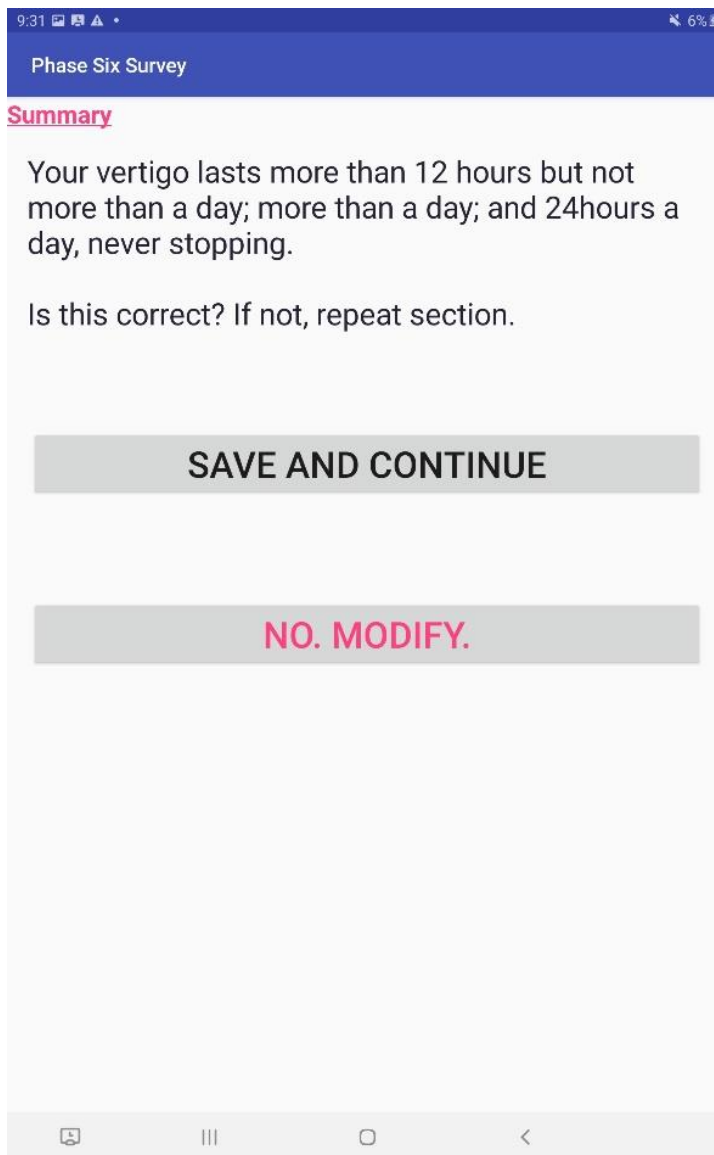


Figure 39 Summary of this section

The fourth section includes 12 questions asks about patients' symptom triggering method, which shows in Figure 40. Figure 41-52 show the questions in this section. Figure 53 is the summary of patients' answers.

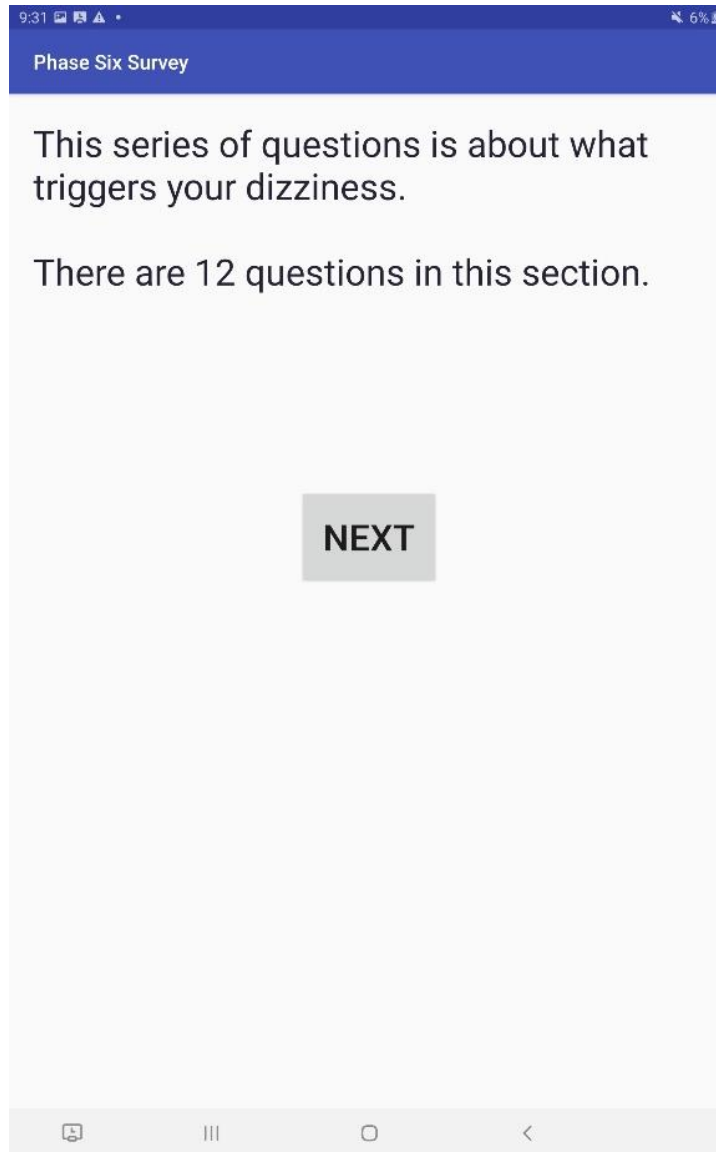


Figure 40 Introduction of fourth section



9:31 6% 6%

Phase Six Survey

1 of 12

Is your vertigo typically made worse or triggered by sitting up or standing up?

Yes

No

PREVIOUS NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile survey application. At the top, there is a blue header bar with the text 'Phase Six Survey'. Below the header, the status bar shows the time '9:31' and battery level '6%'. The main content area is white and contains a question: 'Is your vertigo typically made worse or triggered by sitting up or standing up?'. Below the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area, there are two grey buttons labeled 'PREVIOUS' and 'NEXT'. At the very bottom of the screen, there is a navigation bar with four icons: a back arrow, a home icon, a search icon, and a forward arrow.

Figure 41 First question of this section

9:33 6%

Phase Six Survey

2 of 12

Is your vertigo typically made worse or triggered by reaching or bending?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile application interface for a survey. At the top, there is a blue header bar with the text 'Phase Six Survey' and a status bar above it showing the time '9:33' and battery level '6%'. Below the header, the text '2 of 12' is displayed in the top right corner. The main content area contains a question: 'Is your vertigo typically made worse or triggered by reaching or bending?'. Below the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area, there are two grey rectangular buttons labeled 'PREVIOUS' and 'NEXT'. At the very bottom of the screen is a light grey navigation bar with four icons: a square, three vertical bars, a circle, and a left-pointing chevron.

Figure 42 Second question of this section

9:33 6% 6%

Phase Six Survey

3 of 12

Is your vertigo typically made worse or triggered by tilting your head back?

Yes

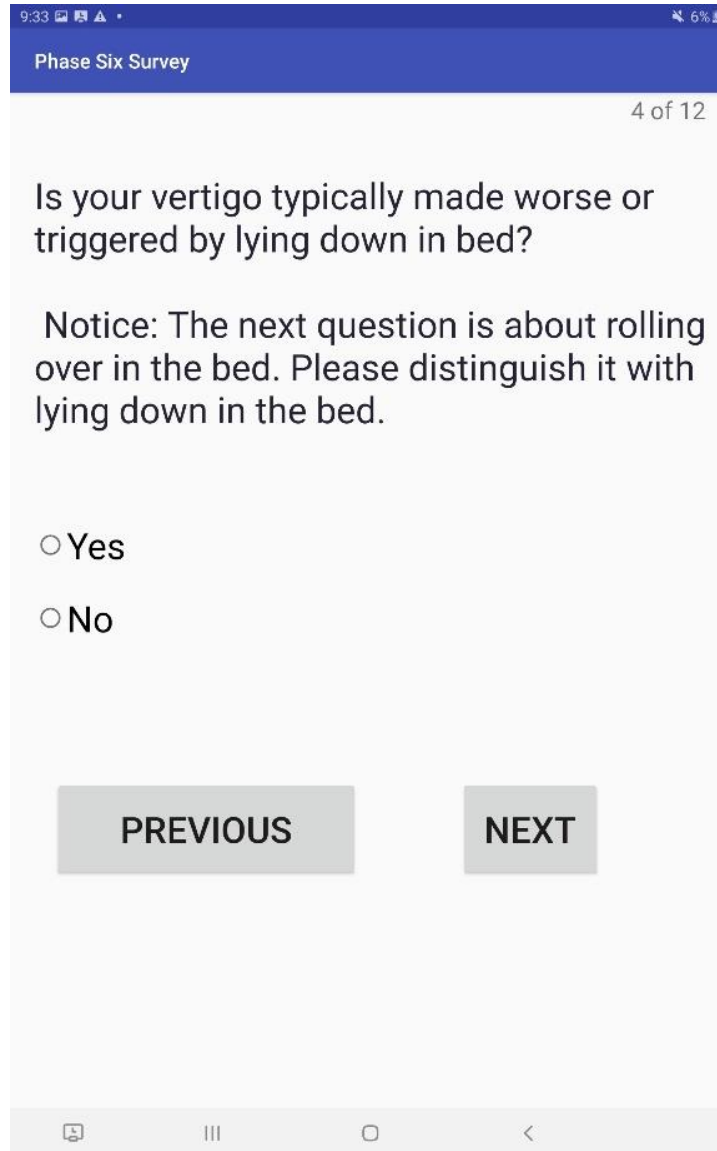
No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 43 Third question of this section



9:33 6%

Phase Six Survey

4 of 12

Is your vertigo typically made worse or triggered by lying down in bed?

Notice: The next question is about rolling over in the bed. Please distinguish it with lying down in the bed.

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 44 4<sup>th</sup> question of this section

9:34 6% 5 of 12

Phase Six Survey

5 of 12

Is your vertigo typically made worse or triggered by rolling over or turning in bed?

Yes

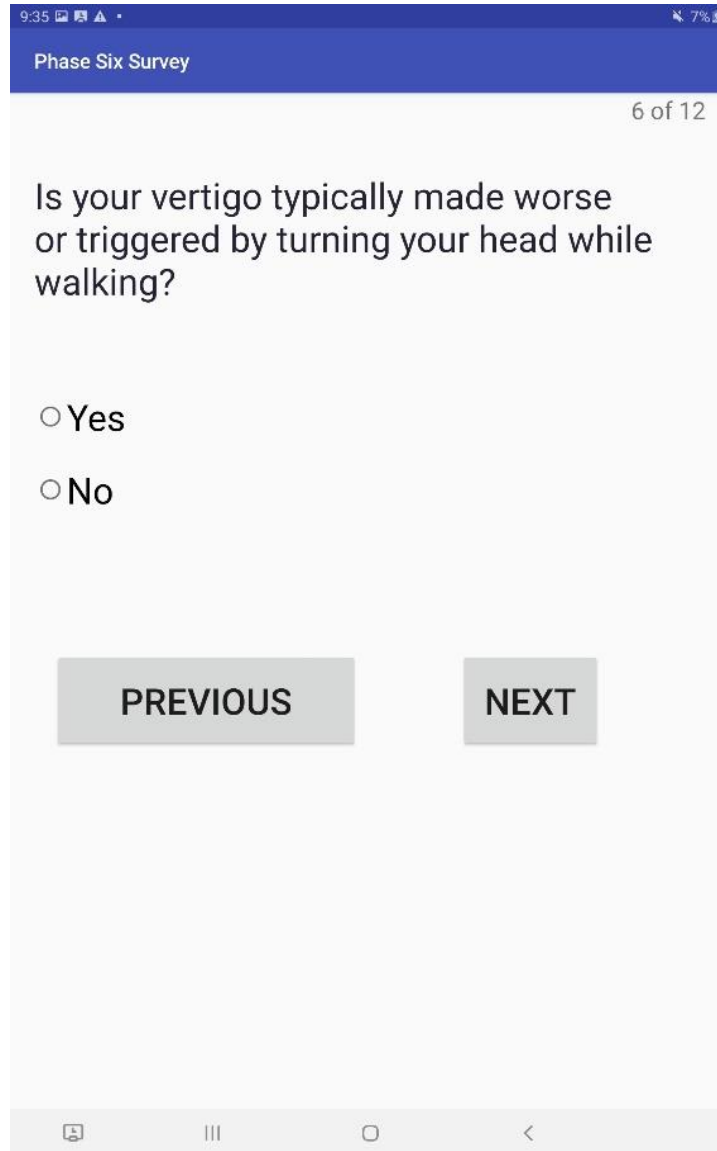
No

PREVIOUS NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile survey application. At the top, there is a blue header bar with the text 'Phase Six Survey'. Below the header, the status bar shows the time '9:34', battery level '6%', and '5 of 12' questions. The main content area contains a question: 'Is your vertigo typically made worse or triggered by rolling over or turning in bed?'. Below the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area are two grey buttons labeled 'PREVIOUS' and 'NEXT'. The very bottom of the screen shows a standard Android navigation bar with icons for back, home, search, and forward.

Figure 45 5<sup>th</sup> question of this section



9:35 7%

Phase Six Survey

6 of 12

Is your vertigo typically made worse or triggered by turning your head while walking?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 46 6<sup>th</sup> question of this section



9:35 7% 7 of 12

Phase Six Survey

7 of 12

Is your vertigo typically made worse or triggered by supermarket aisles?

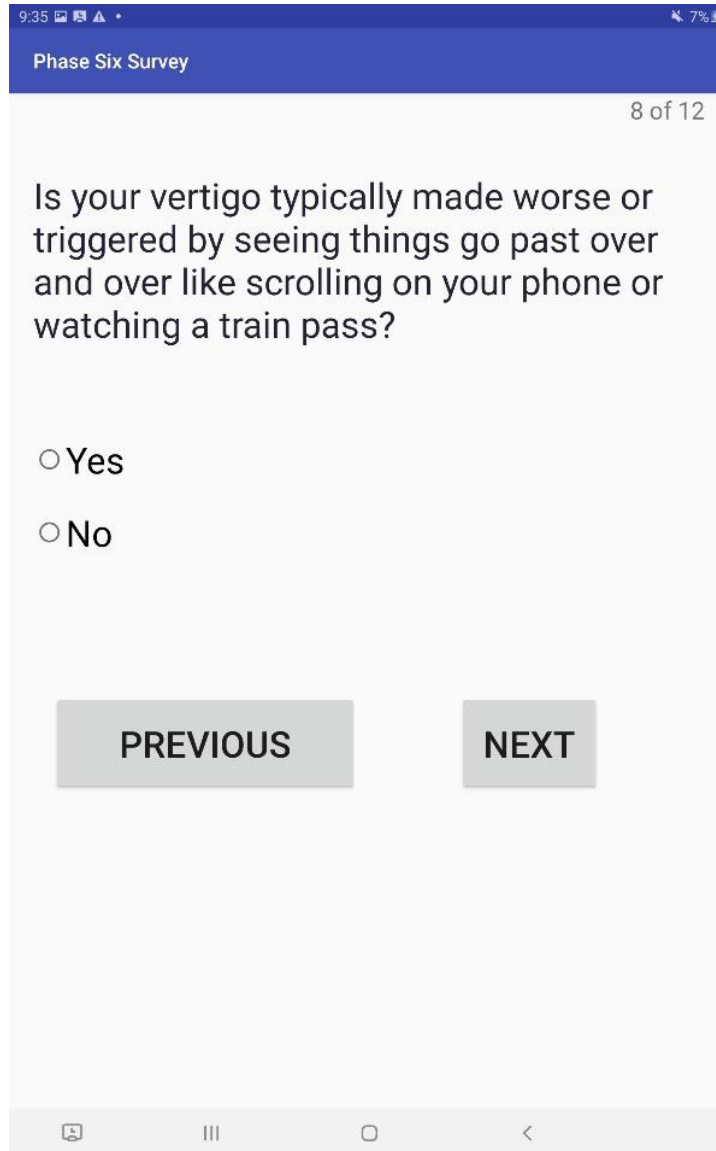
Yes

No

PREVIOUS NEXT

Navigation icons: back, home, search, forward

Figure 47 7th question of this section



9:35 7%

Phase Six Survey

8 of 12

Is your vertigo typically made worse or triggered by seeing things go past over and over like scrolling on your phone or watching a train pass?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, app, forward

Figure 48 8<sup>th</sup> question of this section



9:35 7%

Phase Six Survey

9 of 12

Is your vertigo typically made worse or triggered by loud sounds?

Yes

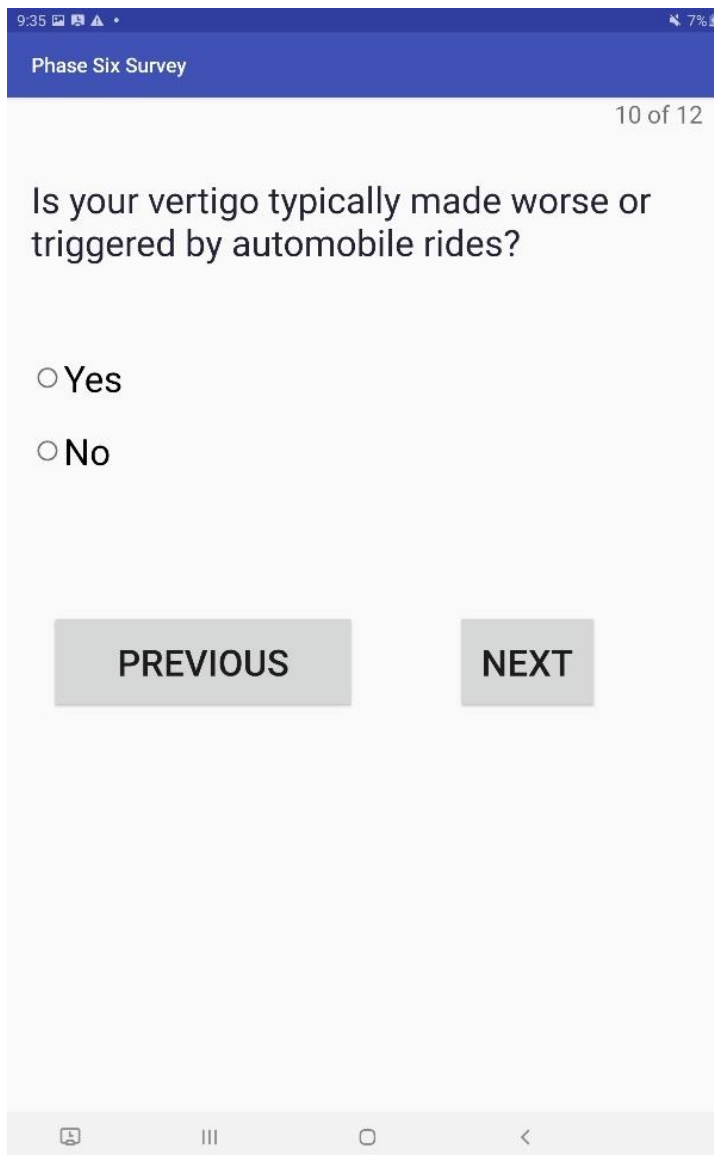
No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 49 9<sup>th</sup> question of this section



9:35 7%

Phase Six Survey

10 of 12

Is your vertigo typically made worse or triggered by automobile rides?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 50 10<sup>th</sup> question of this section

9:35 7%

Phase Six Survey

11 of 12

Is your vertigo typically made worse or triggered by walking on uneven ground?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile survey application. At the top, there is a blue header bar with the text 'Phase Six Survey' and a status bar above it showing the time '9:35' and battery level '7%'. Below the header, the text '11 of 12' indicates the current question number. The main content area contains a question: 'Is your vertigo typically made worse or triggered by walking on uneven ground?'. Below the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area are two grey rectangular buttons labeled 'PREVIOUS' and 'NEXT'. At the very bottom of the screen is a navigation bar with four icons: a back arrow, a home icon, a search icon, and a forward arrow.

Figure 51 11<sup>th</sup> question of this section

9:36 7%

Phase Six Survey

12 of 12

Is your vertigo typically made worse or triggered by driving a car at night? (especially in dark surroundings)

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 52 12<sup>th</sup> question of this section

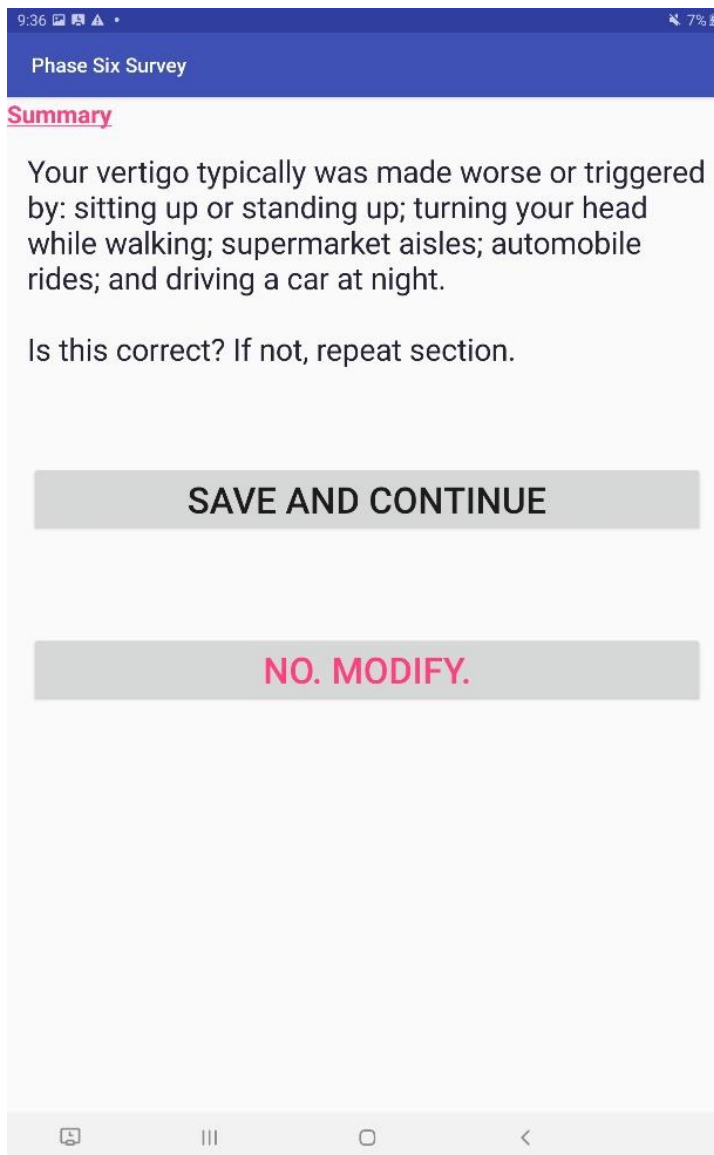


Figure 53 Summary of fourth section

The fifth section asks about patients' ear conditions, which has five questions. The instruction page shows in Figure 54. Figure 55-59 show the questions in this section.

Figure 60 is the summary page of this section.

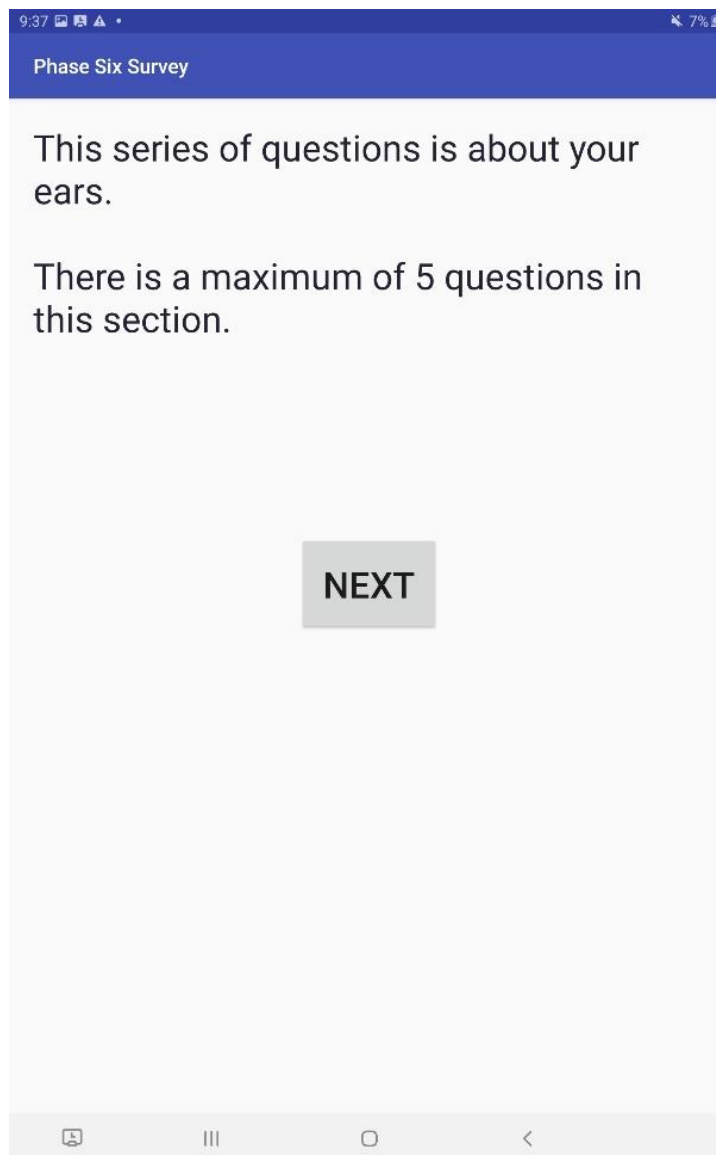


Figure 54 Introduction of fifth section

9:38 7%

Phase Six Survey

1 of 5

Do you have ear pain?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, app, forward

Figure 55 First question of this section

9:38 7%

Phase Six Survey

2 of 5

Do you get an ear infection at least once a year?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, app, forward

Detailed description: This is a screenshot of a mobile application interface for a survey. At the top, there is a blue header bar with the text 'Phase Six Survey'. Below the header, the status bar shows the time '9:38' and battery level '7%'. The main content area is white and contains the question 'Do you get an ear infection at least once a year?'. Below the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area, there are two grey rectangular buttons labeled 'PREVIOUS' and 'NEXT'. The very bottom of the screen shows a standard Android navigation bar with icons for back, home, and app drawer.

Figure 56 Second question of this section



9:38 7%

Phase Six Survey

3 of 5

Do you hear a ringing, buzzing, hissing, or other noise in ONE EAR ONLY or ONE EAR MORE THAN THE OTHER?

Yes

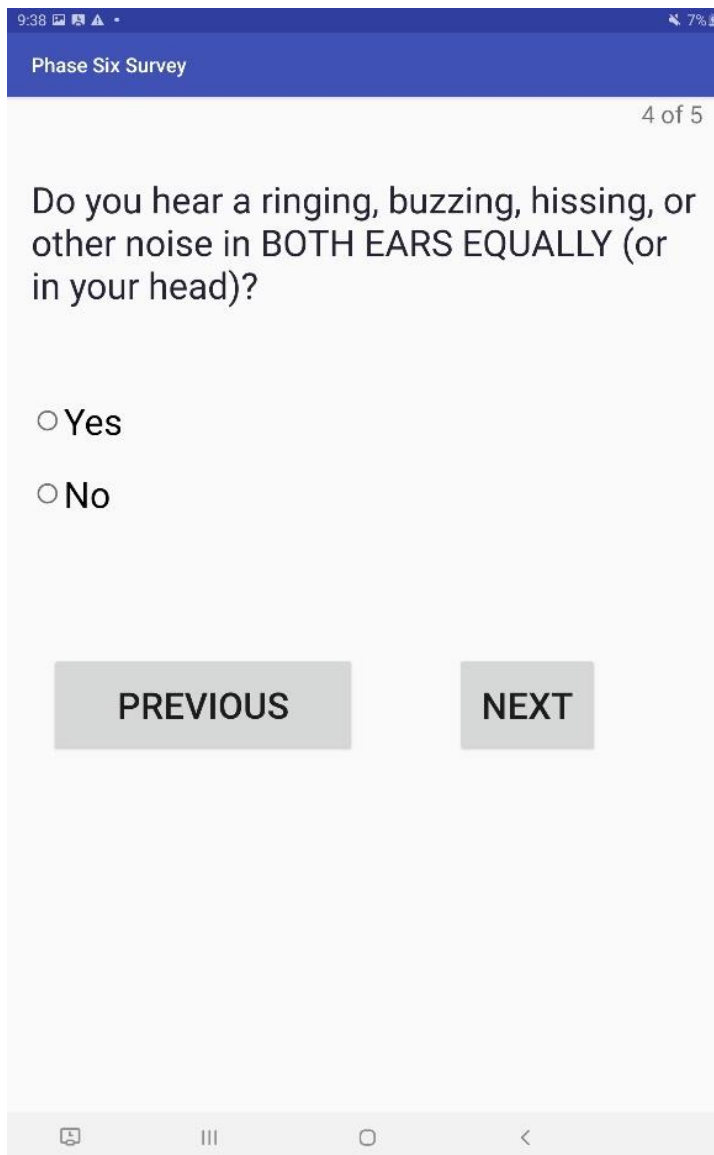
No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 57 Third question of this section



9:38 7%

Phase Six Survey

4 of 5

Do you hear a ringing, buzzing, hissing, or other noise in BOTH EARS EQUALLY (or in your head)?

Yes

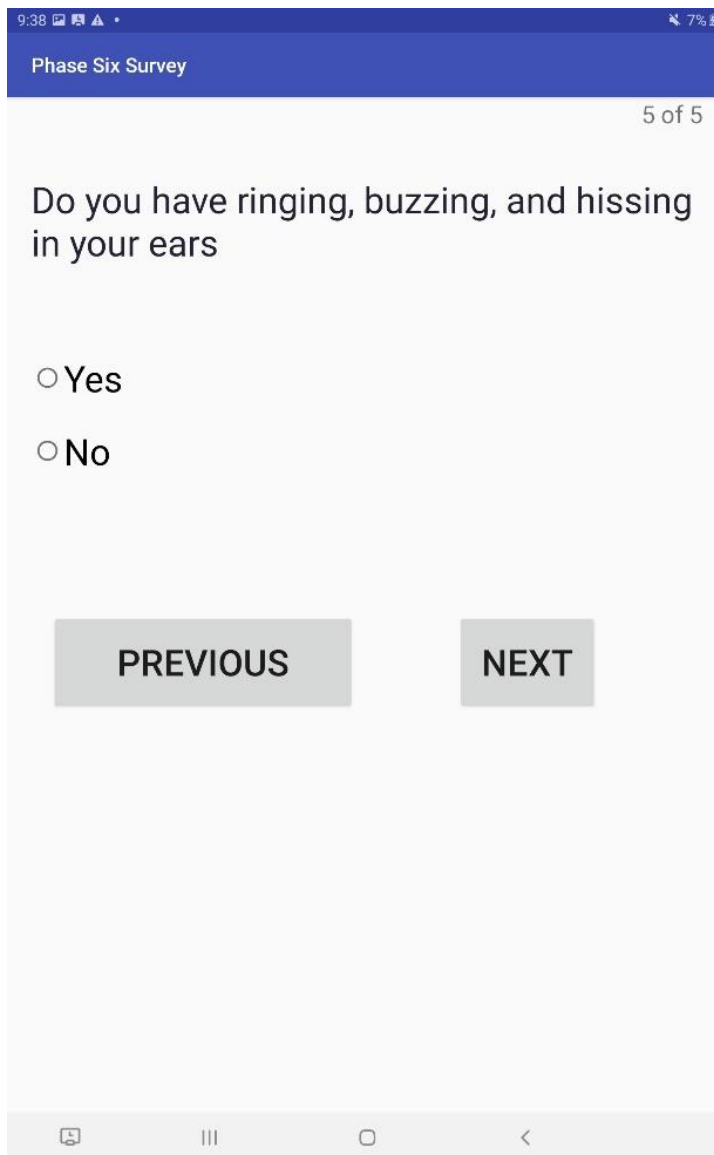
No

PREVIOUS

NEXT

Navigation icons: back, home, recent apps, forward

Figure 58 4<sup>th</sup> question of this section



9:38 7%

Phase Six Survey

5 of 5

Do you have ringing, buzzing, and hissing in your ears

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, recent apps, search, forward

Figure 59 5<sup>th</sup> question of this section

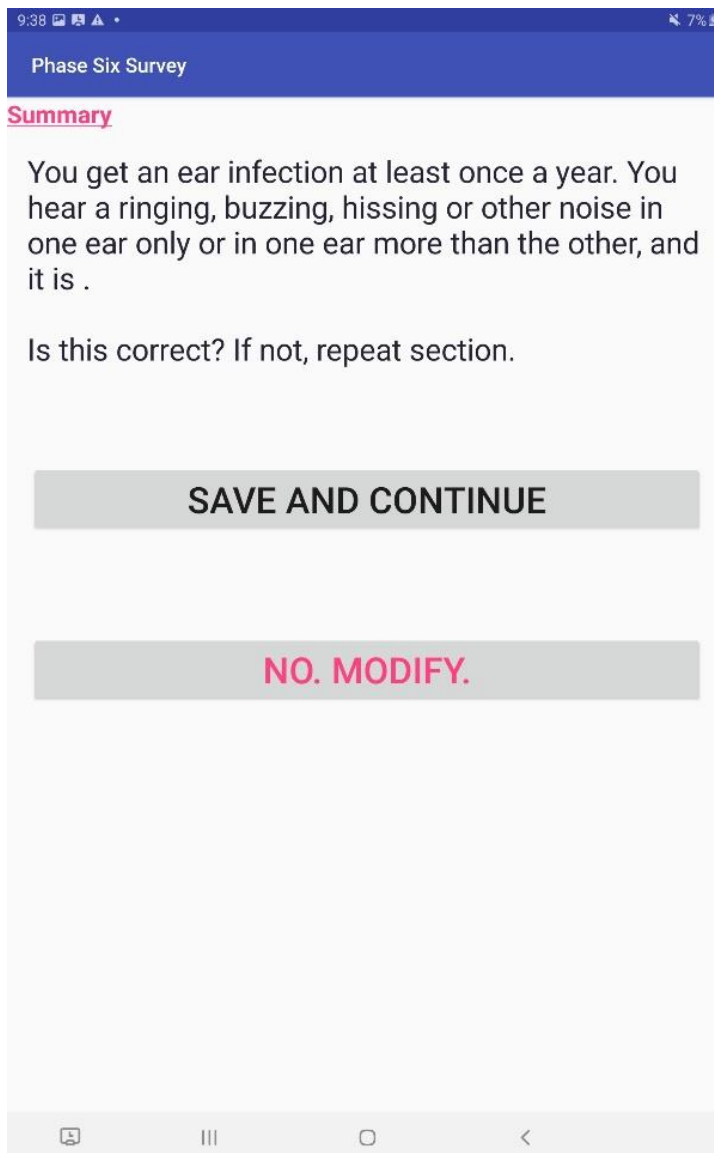


Figure 60 Summary of fifth section

The seventh section includes 10 questions. The topic of this section is headache-associated questions. Figure 61 is the introduction of this section. Figure 62-71 are the questions. The summary of answers is shown in Figure 72.

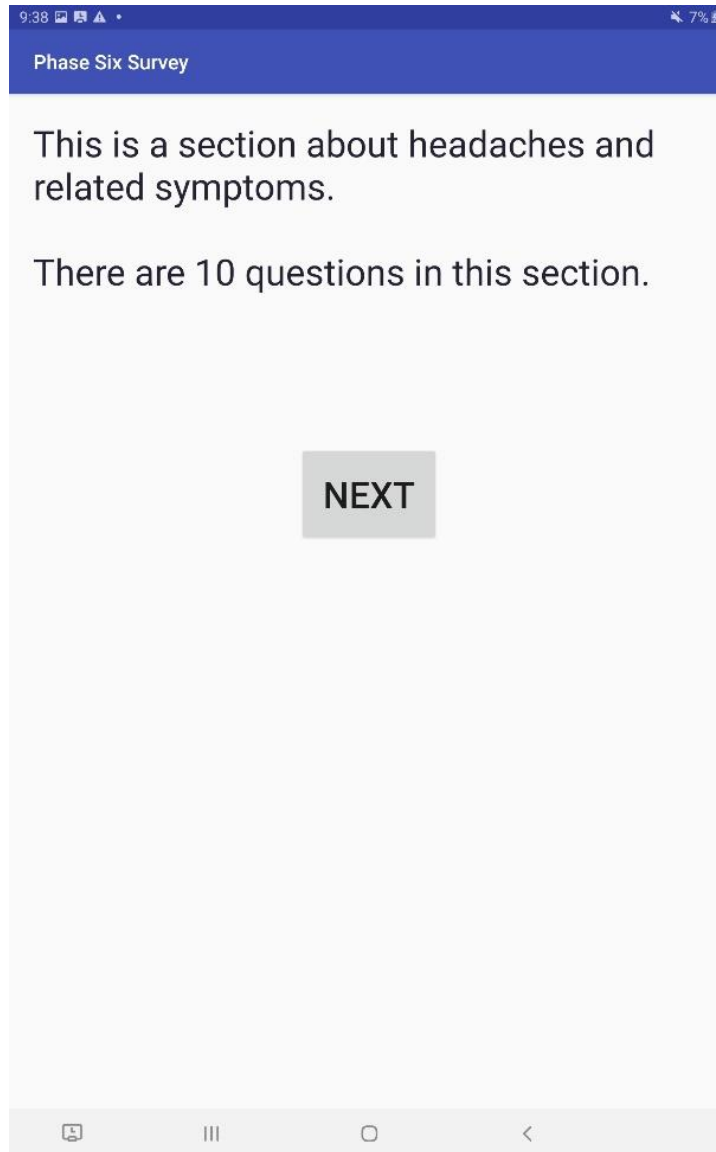


Figure 61 Introduction of seventh section

9:38 7%

Phase Six Survey

1 of 10

Have you had a total of 5 or more bad headaches in your lifetime?

Yes

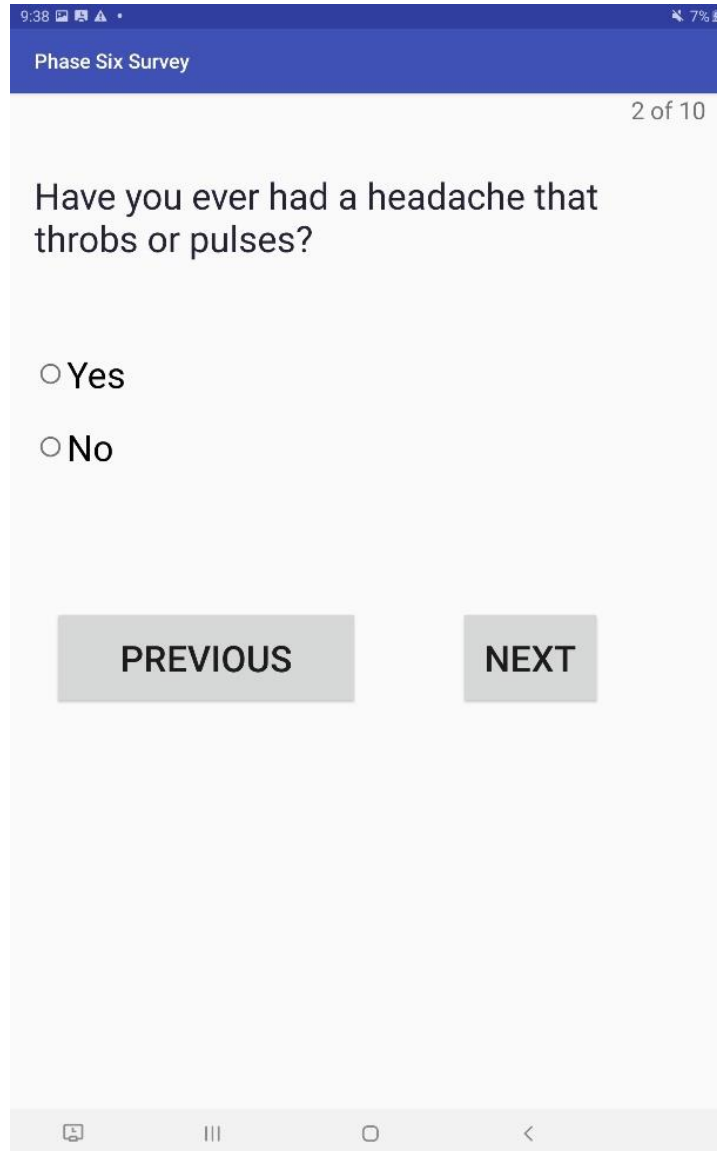
No

PREVIOUS NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile application interface for a survey. At the top, there is a dark blue header bar with the text 'Phase Six Survey' in white. Above this bar, the status bar shows the time '9:38' and battery level '7%'. Below the header, the text '1 of 10' is displayed in the top right corner. The main content area is light gray and contains a question: 'Have you had a total of 5 or more bad headaches in your lifetime?'. Below the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area, there are two gray rectangular buttons labeled 'PREVIOUS' and 'NEXT'. At the very bottom of the screen is a white navigation bar with four icons: a square, three vertical bars, a circle, and a left-pointing arrow.

Figure 62 The first question of this section



9:38 7%

Phase Six Survey

2 of 10

Have you ever had a headache that throbs or pulses?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, app, forward

Figure 63 The second question of this section

9:38 7%

Phase Six Survey

3 of 10

Have you ever had increased sensitivity to light with a headache?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, app, forward

Figure 64 The third question of this section



9:38 7%

Phase Six Survey

4 of 10

Have you ever had increased sensitivity to sounds with a headache?

Yes

No

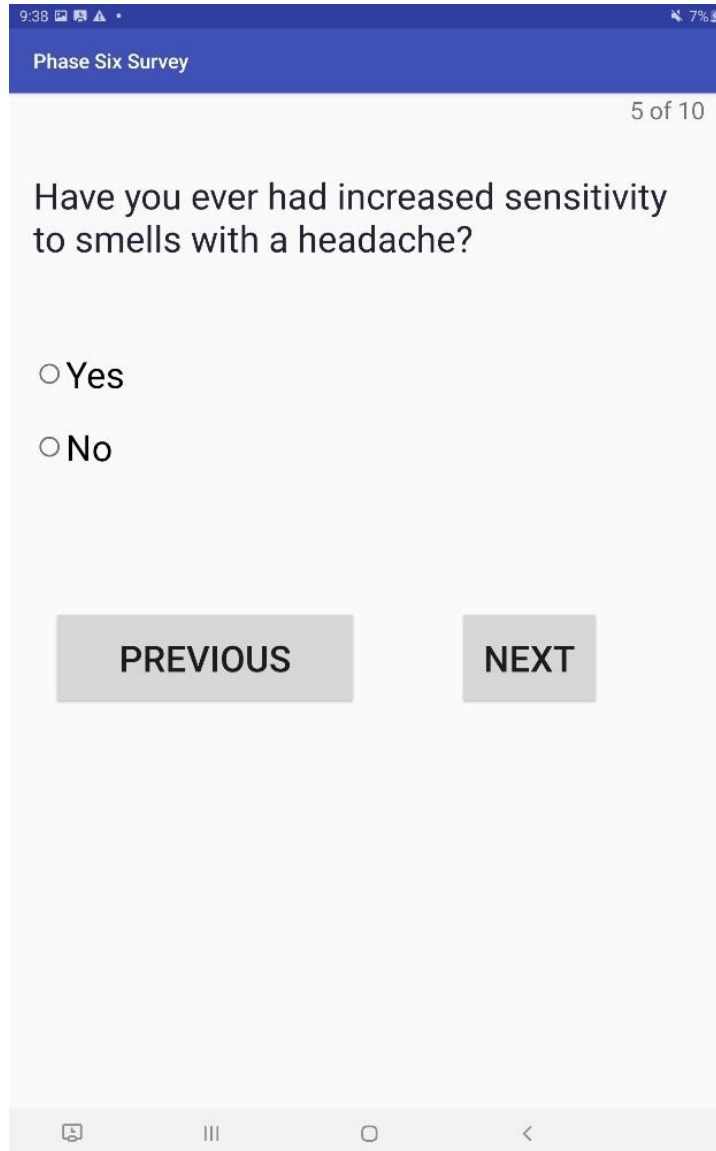
PREVIOUS

NEXT

Navigation icons: back, home, app, forward

Detailed description: This is a screenshot of a mobile application interface for a survey. At the top, there is a blue header bar with the text 'Phase Six Survey' on the left and '4 of 10' on the right. Below the header, the main content area is white and contains a question: 'Have you ever had increased sensitivity to sounds with a headache?'. Underneath the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area, there are two grey rectangular buttons labeled 'PREVIOUS' and 'NEXT'. The very bottom of the screen shows a standard Android navigation bar with icons for back, home, and app drawer.

Figure 65 The 4<sup>th</sup> question of this section



9:38 7%

Phase Six Survey

5 of 10

Have you ever had increased sensitivity to smells with a headache?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 66 The 5<sup>th</sup> question of this section

9:39 7%

Phase Six Survey

6 of 10

Have you ever had nausea or vomiting with a headache?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, app, forward

Figure 67 The 6<sup>th</sup> question of this section

9:39 7%

Phase Six Survey

7 of 10

Have you ever had your vertigo associated with a headache?

Yes

No

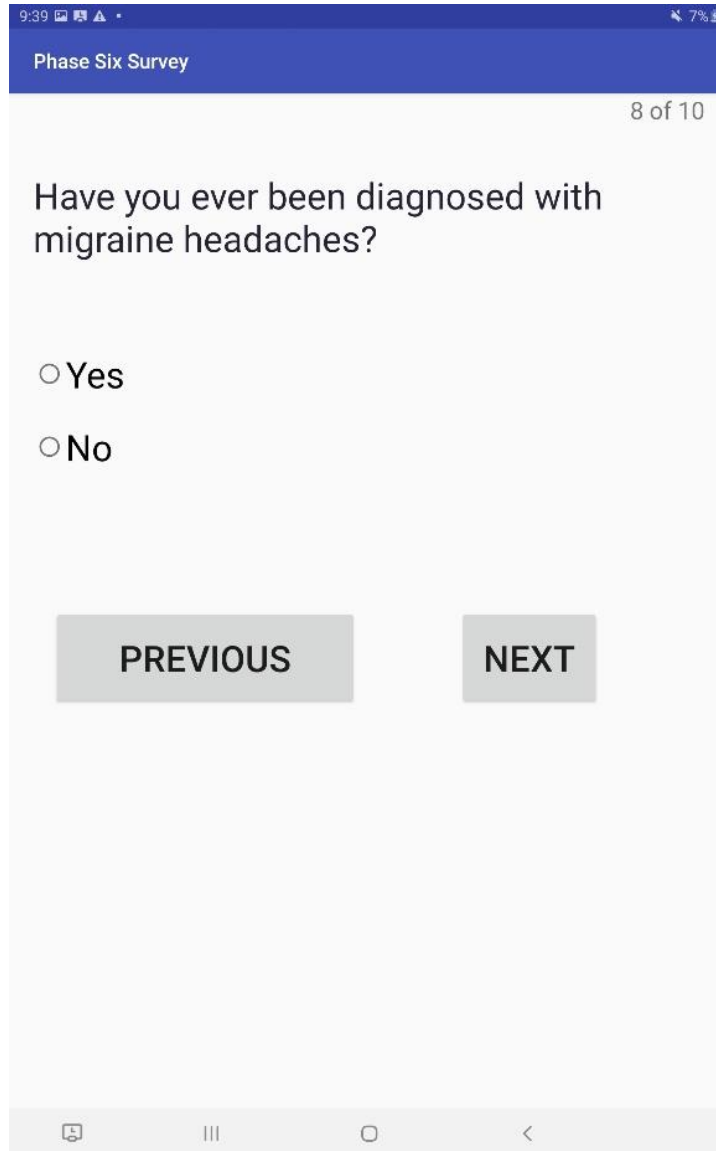
PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile survey application. At the top, there is a blue header bar with the text 'Phase Six Survey' on the left and '7 of 10' on the right. Below the header, the main content area is white and contains the question 'Have you ever had your vertigo associated with a headache?'. Underneath the question are two radio button options: 'Yes' and 'No'. At the bottom of the question area, there are two grey rectangular buttons labeled 'PREVIOUS' and 'NEXT'. The very bottom of the screen shows a standard Android navigation bar with icons for back, home, search, and forward.

Figure 68 The 7<sup>th</sup> question of this section



9:39 7%

Phase Six Survey

8 of 10

Have you ever been diagnosed with migraine headaches?

Yes

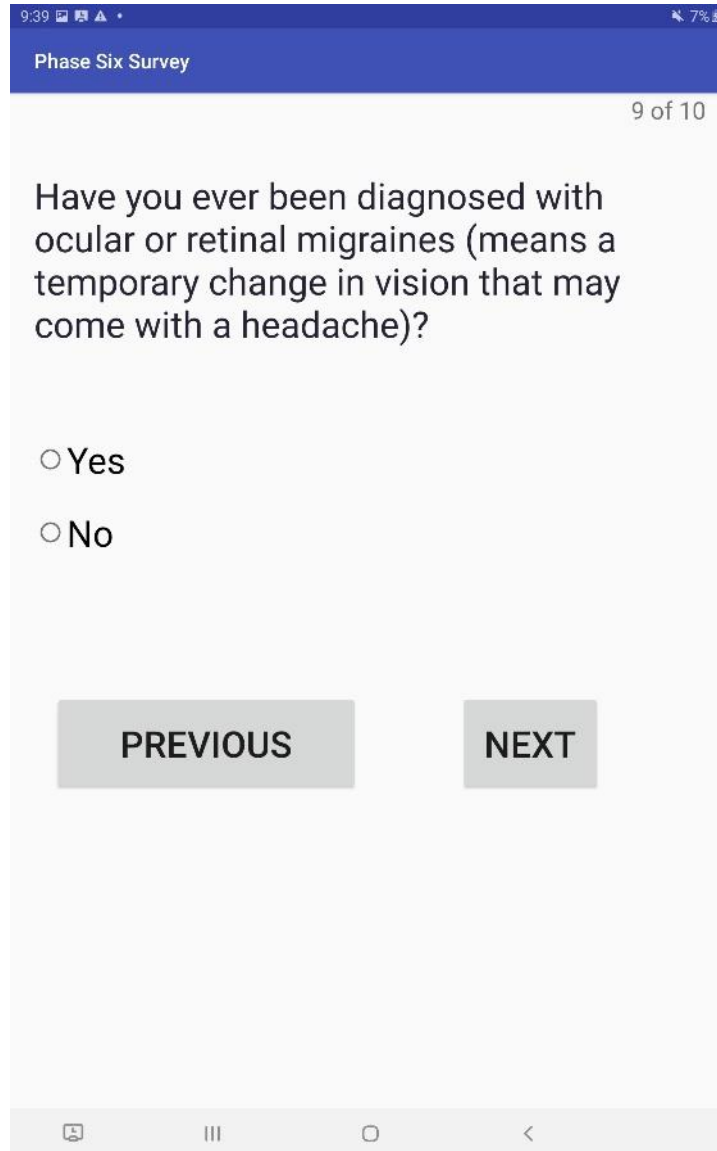
No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 69 The 8<sup>th</sup> question of this section



9:39 7%

Phase Six Survey

9 of 10

Have you ever been diagnosed with ocular or retinal migraines (means a temporary change in vision that may come with a headache)?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Figure 70 The 9<sup>th</sup> question of this section

9:39 7%

Phase Six Survey

10 of 10

Did you get carsick as a child?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, app, forward

Figure 71 The 10<sup>th</sup> question of this section

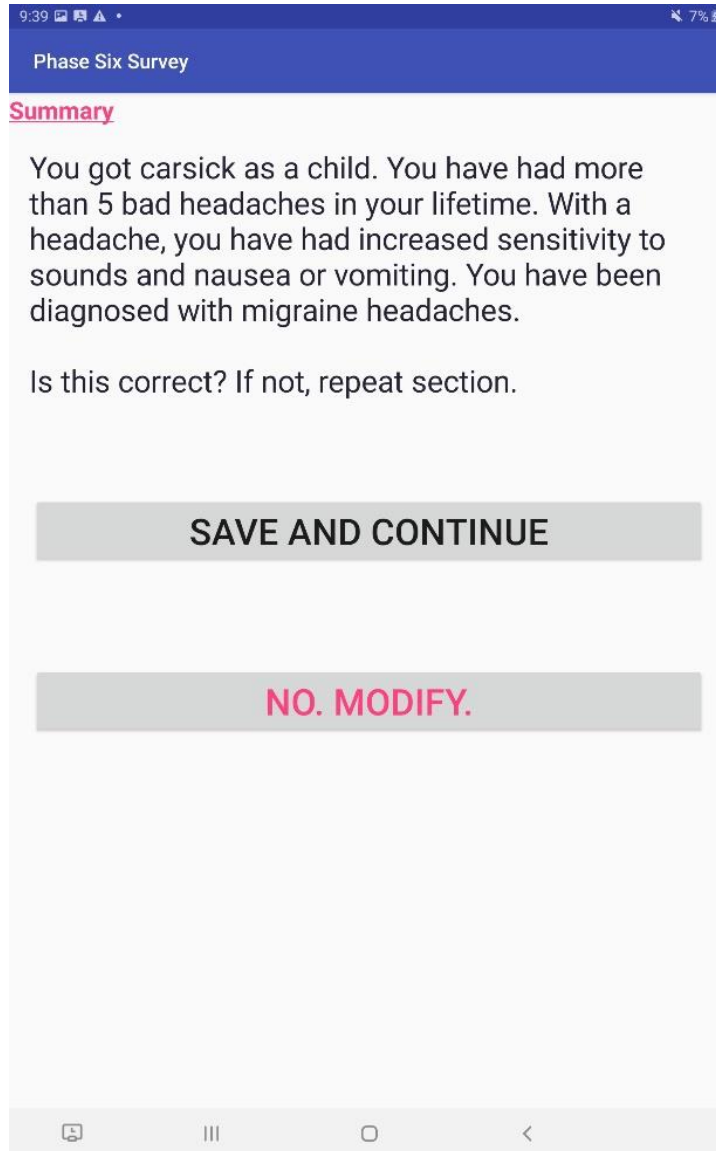


Figure 72 Summary of this section



Figure 73 shows the last section asks about patients' medical history and the number of questions is two. Figures 74 and 75 ask questions about the patients' medical history. Figure 76 is the ending page of the survey. The database recording answers will be generated once patients press "done" button.

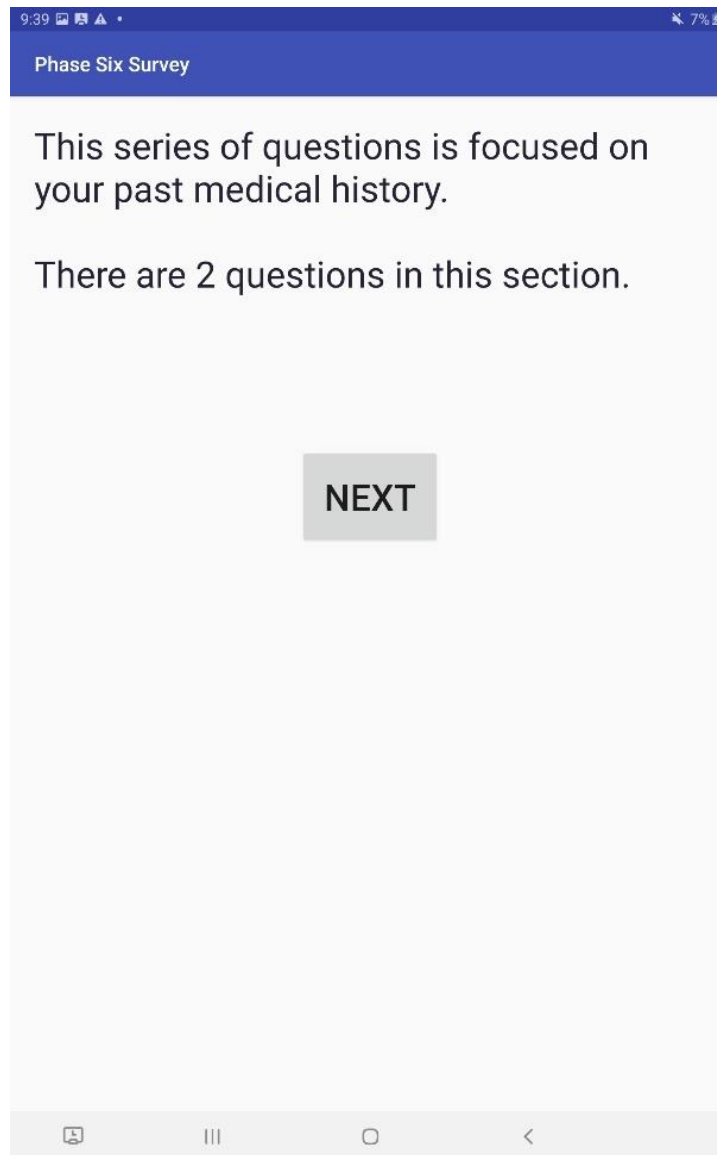


Figure 73 Introduction of last section

9:39 7%

Phase Six Survey

1 of 2

Have you had a hip or knee replacement?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, search, forward

Detailed description: This is a screenshot of a mobile application interface for a survey. At the top, there is a blue header bar with the text 'Phase Six Survey'. Below the header, the status bar shows the time '9:39' and battery level '7%'. The main content area is white and contains the question 'Have you had a hip or knee replacement?'. Below the question are two radio button options: 'Yes' and 'No'. At the bottom of the main content area, there are two grey rectangular buttons labeled 'PREVIOUS' and 'NEXT'. The very bottom of the screen shows a standard Android navigation bar with icons for back, home, search, and forward.

Figure 74 The 1<sup>st</sup> question of this section

9:39 7%

Phase Six Survey

2 of 2

Have you had chemotherapy?

Yes

No

PREVIOUS

NEXT

Navigation icons: back, home, app, forward

Detailed description: This is a screenshot of a mobile application interface for a survey. At the top, there is a blue header bar with the text 'Phase Six Survey'. Below the header, the status bar shows the time '9:39' and battery level '7%'. The main content area is white and contains the question 'Have you had chemotherapy?' followed by two radio button options: 'Yes' and 'No'. At the bottom of the question area, there are two grey rectangular buttons labeled 'PREVIOUS' and 'NEXT'. The very bottom of the screen shows a standard Android navigation bar with icons for back, home, and app drawer.

Figure 75 Questions in seventh section

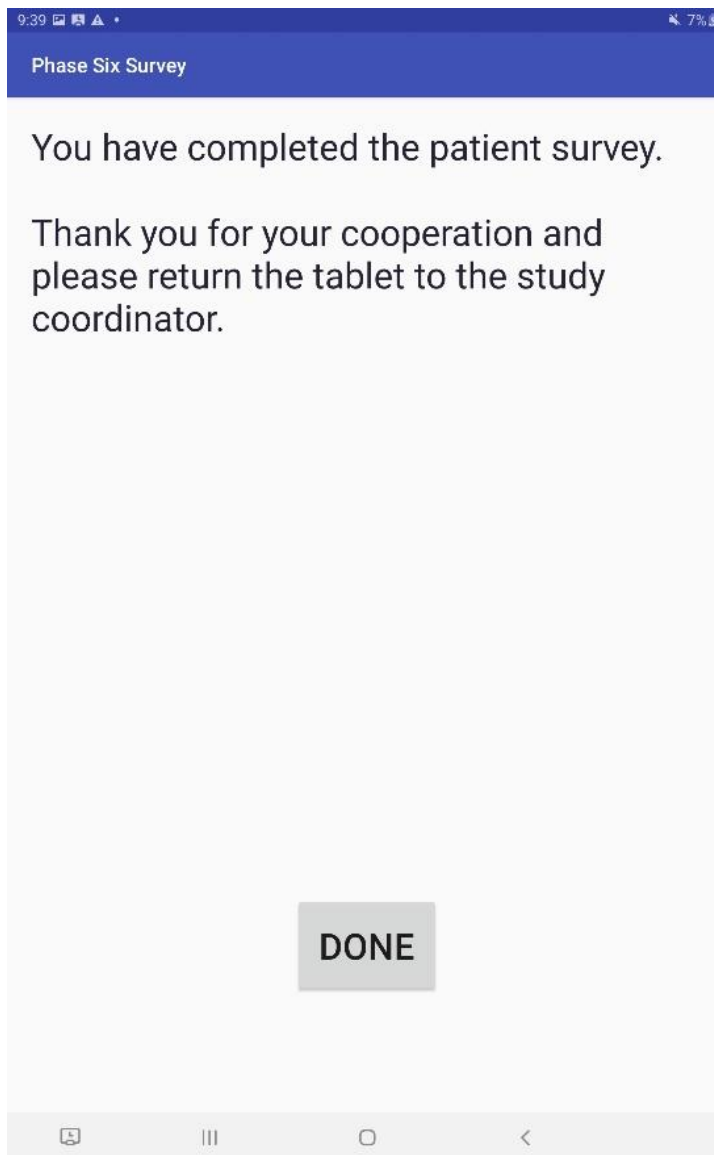


Figure 76 End page of the patient survey