A STEADY-STATE VISUAL EVOKED POTENTIAL-BASED BRAIN COMPUTER INTERFACE SYSTEM FOR PATIENTS WITH MOTOR DISABILITIES

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JANUARY 2017

A STEADY-STATE VISUAL EVOKED POTENTIAL-BASED BRAIN COMPUTER INTERFACE SYSTEM FOR PATIENTS WITH MOTOR DISABILITIES

By

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A dissertation submitted to the
Department of Mechatronics and Biomedical Engineering,
Lee Kong Chian Faculty of Engineering and Science,
Universiti Tunku Abdul Rahman,
In partial fulfillment of the requirements for the degree of
Master of Engineering Science
January 2017

ABSTRACT

Brain Computer Interfaces (BCIs) offer the possibility for paralyzed people to communicate and control devices. The current work aims at developing a steady-state visual evoked potential (SSVEP)-based BCI system for patients with motor disabilities. Two Graphical User Interfaces (GUIs) were developed in the present study – a five-class word-based GUI and a six-class pictorial-based GUI. The former features a phrase selection system with a list of words commonly used by patients to express their needs for daily living. The system was initially tested on healthy subjects to assess the efficacy of the system before tested on patients with motor disabilities. The first word-based GUI was designed for a 25-year-old patient. LED stimulators were used to replace the LCD stimulators in the original design to enhance the SSVEP responses of the patient. The system was also tweaked to further include careful selection of stimulation frequencies to match the special responses of the patient. The highest classification accuracy he achieved was 61.1%. The second pictorial-based GUI, on the other hand, was designed for a 4-year-old patient with the inclusion of two main categories besides the needs for daily living: entertainment and feelings expression. The highest classification accuracy he achieved was 83.3%.

ACKNOWLEDGEMENT

I would like to express my greatest appreciation to my supervisor Prof. Goh Sing Yau and my co-supervisor Dr. Mok Siew Ying for their relentless support and guidance throughout my study. Without them, I could not have made it through these years. Special thanks go to the entire BCI research team for their assistance and excellent teamwork. I am also very thankful to my university for providing me with facilities, services, and equipment necessary to conduct my study.

I would also like to extend my appreciation to the patients and their caregivers for their valuable feedback and cooperation. Finally, all of my achievement is only possible with the unwavering love and moral support from my family.

APPROVAL SHEET

This dissertation entitled **"A STEADY-STATE VISUAL EVOKED POTENTIAL-BASED BRAIN COMPUTER INTERFACE SYSTEM FOR PATIENTS WITH MOTOR DISABILITIES"** was prepared by MAH WAI LAI and submitted as partial fulfillment of the requirements for the degree of Master of Engineering Science at Universiti Tunku Abdul Rahman.

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It is hereby certified that **MAH WAI LAI** (ID No: **13UEM07459**) has completed this dissertation entitled "**A STEADY-STATE VISUAL EVOKED POTENTIAL-BASED BRAIN COMPUTER INTERFACE SYSTEM FOR PATIENTS WITH MOTOR DISABILITIES**" under the supervision of **Prof. Dato' Ir. Dr. GOH SING YAU** (Supervisor) from the Department of Mechanical and Material Engineering, Lee Kong Chian Faculty of Engineering and Science, and **Dr. MOK SIEW YING** (Co-Supervisor) from the Department of Mechatronics and BioMedical Engineering, Lee Kong Chian Faculty of Engineering and Science.

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(MAH WAI LAI)

DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

Name ______________________________

Date ______________________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADC	Analog-to-Digital Converter
BCI	Brain Computer Interface
CRT	Cathode Ray Tube
EEG	Electroencephalogram
ERS/ERD	Event–Related Synchronization/ Desynchronization
XML	EXtensible Markup Language
FFT	Fast Fourier Transform
GUI	Graphical User Interface
LCD	Liquid Crystal Display
LED	Light Emitting Diode
RVS	Repetitve Visual Stimuli
SBR	Signal-to-Baseline Ratio
SCP	Slow Cortical Potential
SSVEP	Steady-State Visual Evoked Potential
USB	Universal Serial Bus

CHAPTER 1

INTRODUCTION

A Brain Computer Interface (BCI) provides a direct communication pathway between neural activity and external devices, such as mouse cursors, wheelchairs, and robotic limbs. The main goal of the BCI is to help patients with motor disabilities to restore certain functionalities such as communication and mobility.

Over the past decades, different sources of neural signals such as P300, slow cortical potential (SCP) and steady-state evoked potential (SSVEP) have been used in the BCI research. Among the various systems, BCI based on SSVEPs gained higher popularity as it has been shown to have information transfer rate and higher accuracy, as well as short user training time.

Although promising, large variations have been reported in the classification performance of BCI users (Guger et al., 2012; Allison and Neuper, 2010). Accordingly, a substantial portion of people experienced troubles with BCIs and hence yielded low performance, while some could not even use a BCI system. It has been suggested that these people do not produce the specific brain activity patterns needed for the particular BCI approach (Allison and Neuper, 2010). Other factors that also contribute to low classification performance include excessive muscle artifacts and a lack of proficiency on how to use a BCI system (Müller-Putz et al., 2005; Allison and

Neuper, 2010). While most of these measures were based on healthy subjects, patients may have worse performance dynamics due to medications, visual deficits, partial brain damage, neuropsychiatric conditions and other factors (Piccione et al., 2006; Ortner et al., 2011; Guger et al., 2012; Schreuder et al., 2013). All the above suggests that there is no standard BCI that works for all users and adaptation to individual users is the key element in this regard.

The goal of the current study is to develop a working SSVEP-based BCI communication system for patients with motor disabilities. Two Graphical User Interfaces (GUIs) have been custom designed – one using words and another using pictorial representations for selections. The content of the built-in dictionary was also customized according to the patients' need to facilitate selections. To enhance the BCI performance, the system was tweaked further with certain adaptations in the system design and parameters. Such adaptations have enabled the two patients to obtain an acceptable level of BCI control which was otherwise impossible with the standard BCI system.

The rest of the dissertation is structured as below:

Chapter 2 provides a literature review on the BCI, the SSVEP and the communication system.

Chapter 3 describes the design of the GUIs and the dictionary for the BCI communication system. The experimental paradigm and the data analysis methods are also explained.

Chapter 4 presents the results of the BCI tests on healthy subjects as well as the two patients with motor disabilities.

Chapter 5 discusses the results obtained and the adaptations made to yield the working BCIs.

Chapter 6 concludes the dissertation with a summary of the research findings. Several suggestions for future work are also discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Brain Computer Interface (BCI)

The history of BCI began with the discovery of EEG by the German psychiatrist Hans Berger in 1924. The term BCI, however, was only introduced in the 1970s by Dr. Vidal when he showed that visual evoked potentials could be used to control the movement of a cursor through a two-dimensional maze (Vidal, 1973).

BCI is an alternative communication method based on neural activity and it does not depend on the peripheral nerves and muscles (Wolpaw et al., 2000). It thus serves as an alternative communication method for patients with motor disabilities. The detected brain signals could be translated into various actions, such as selecting letters using virtual keyboards, playing games, moving robotic arms, controlling internet browsers or wheelchairs (Farwell and Donchin, 1988; Chapin et al., 1999; Wolpaw et al., 2000; Obermaier et al., 2003; Carmena et al, 2003; Wolpaw and McFarland, 2004; Lalor et al., 2005; Galán et al., 2008; Mugler et al., 2010; Perego et al., 2010; Pires et al., 2011; Hwang et al., 2012).

The neural signals required for the BCI system can be recorded using invasive or non-invasive techniques. The invasive technique requires implantation of electrodes into the grey matter of the brain through surgery. It is targeted at providing new functionality to the paralyzed patients. This method provides good signal resolution. However, the building up of scar tissue and the needs for surgery rendered this method less popular for BCI applications.

On the other hand, the non-invasive technique was widely used as recordings could be easily performed by placing the electrodes directly over the scalp following the International 10-20 system (Jasper, 1958). However, it showed poor signal resolution as the voltage produced by the neurons needed to penetrate through the scalp, skin, skull and meninges before reaching the electrodes. Therefore, non-invasive BCI system normally requires a built-in amplifier to increase the EEG amplitude and an analog-to-digital converter (ADC) to digitize the signals in a more accurate way (Nicolas-Alonso and Gomez-Gil, 2012).

The electrophysiological sources of non-invasive BCIs include event-related synchronization/ desynchronization (ERS/ERD), slow cortical potentials (SCP), steady-state visual evoked potentials (SSVEP), sensorimotor rhythms and P300 evoked potentials (Bashashati et al., 2007). In the current study, SSVEP was used as it has been shown to have higher accuracy (Guger et al., 2012a) and higher information transfer rate compared to other systems and required short/no training time (Amiri et al., 2013).

2.2 Steady-State Visual Evoked Potential (SSVEP)

SSVEP is a direct response that occurs in the primary visual cortex upon receiving a visual stimulus. When the retina is excited by repetitive visual stimuli flashing at a constant frequency, oscillatory activity of the same frequency would be generated (Regan, 1989; Silberstein, 1995). The stimulation frequencies used for triggering SSVEP responses can be categorized into three ranges, which are low (<12 Hz), medium (12-30 Hz) and high frequencies (>30 Hz) (Regan, 1989).

In general, the fundamental and harmonic frequency components are detectable in response to the visual stimulus. For example, when the user focuses at the stimulus flickering at 8 Hz, SSVEP peaks are visible at 8 Hz (fundamental frequency), 16 Hz (second harmonic) and 24 Hz (third harmonic) (Wang et al., 2008).

2.3 SSVEP-based BCI

There are two modes of operation for BCI, which are synchronous or cue-paced BCI and asynchronous or self-paced BCI (Graimann et al., 2010). For the asynchronous BCI, users were allowed to communicate whenever he/she wants, but brain signals need to be analyzed continuously. On the other hand, the synchronous BCI allows users to perform mental task in well-defined time frames. Although users lost the flexibility to communicate beyond the specific time frames, the operation mode of the synchronous BCI makes the system easier to be developed with simpler detection and classification, and is therefore adopted in the current study.

2.4 Design parameters

Several design parameters need to be considered when developing the SSVEP-based BCI system. These include the type of repetitive visual stimuli, the colors and types of visual stimulator, the stimulation frequencies.

2.4.1 Repetitive Visual Stimuli (RVS)

There are three main types of RVS used in the SSVEP-based BCIs (Zhu et al., 2010). The first type of RVS uses light to render the stimulus. The Light source can be LED, fluorescent or Xe lights. These light sources are modulated at specified frequencies using dedicated electronic circuit boards to accurately render any illumination waveforms.

The second type of RVS is the single graphics stimuli. This type of stimuli can be rendered in various shapes such as square, rectangle, or arrow on a computer screen. The stimulation frequency is rendered by having the graphic appear and disappear into the background. The last type of RVS is the pattern reversal stimuli which are rendered with an oscillatory alternation of graphical patterns (ex: checkerboards or line boards) on a computer screen. They contain at least two graphical patterns that alternate at specific number of alternations per second (Odom et al., 2004).

The prevailing view in the BCI literature is that slightly more research studies show that rendered single graphic stimuli using computer screen work better as compared to the pattern reversal (Zhu et al., 2010). In a recent study to compare the performance of plain and checkerboard stimuli, the results showed that the plain stimulus gave significant average increase in SSVEP classification over the checkerboard stimulus (Zerafa et al., 2013). Therefore, the single graphic stimulus is adopted in the current study.

2.4.2 Colors of light stimuli

In the prevailing SSVEP-based BCI literature, six colors were commonly used for the stimulators: red, green, gray, blue, yellow and white (Maggi et al., 2006; Leow et al., 2007; Garcia Molina, 2008; Allison et al., 2008; Singla et al., 2013). The effects of color on the amplitude and frequency of SSVEPs have been reviewed in some of the research papers (Regan, 1966; Cheng et al., 2001; Wu and Yao, 2008; Huang et al., 2009). In the recent years, a critical evaluation on the effects of different colors on SSVEP and system performance has been carried out (Cao et al., 2012; Tello et al., 2014).

White color stimulus in black color background was discovered to give the highest system performance (Cao et al., 2012). As it also minimized the eye strain of the users, this color has been adopted in the present BCI system.

2.4.3 Types of visual stimulator

Other than the previous parameters, the type of stimulator also plays an important role in the system design. The SSVEP responses can be evoked by three different types of stimulators, which are light emitting diode (LED) (Wang et al., 2005, 2010; Hwang et al., 2012), cathode ray tube (CRT) (Cheng and Gao, 1999; Cheng et al., 2002; Allison et al., 2007) and liquid crystal display (LCD) (Bin et al., 2009; Volosyak et al., 2009;). The LCD gives the similar performance as the CRT. As LCDs are now more commonly available compared to CRTs, CRTs were not taking into consideration.

The current study uses both the LCD and LED stimulators. Patients were first tested for their SSVEP responses with LCD stimulators and if the results were unsatisfactory, they were switched over to use the LED stimulators. LCD stimulator is preferred as it does not require an external electronic circuit board to control the flashing of flickers (Wu et al., 2008) and the rendering of flashing boxes on the computer screen is more flexible (Wang et al., 2010).

2.4.4 Frequency selection

Most studies on SSVEP-based BCIs utilized low- and medium-frequency stimuli (Hoffmann et al., 2009). The reason behind the choice is that stimuli with low and medium frequencies evoked SSVEPs with larger amplitudes, making the responses more easily detected. However, it caused tiredness and annoyance to the users.

High-frequency stimuli reduced visual fatigue of the users (Wang et al., 2005; Sakurada et al., 2014). However, the amplitudes of the SSVEPs triggered by high-frequency flickers were significantly smaller. In this study, low and medium frequencies were used for larger SSVEP responses to minimize false classification.

There are further restrictions on the selection of frequency when LCD stimulators are used. In order to generate stable frequencies on a LCD monitor, the stimuli should be selected as divisors of the refresh rate (Volosyak et al., 2009). For instance, for LCD with refresh rate of 60 Hz, if the 15 Hz is selected, second harmonic of 30 Hz and third harmonic of 45 Hz are unsuitable. With this, the difficulty of frequency selection was increased and limited the number of available frequencies to be chosen. For this reason, LED stimulators were employed in cases where the number of available frequencies with LCD stimulators was limited.

2.5 Communication applications

Over many years, the speller (Friman et al., 2007; Cecotti et al., 2010; Volosyak et al., 2011; Cao et al., 2011; Vilic et al., 2013; See et al., 2013; Chen et al., 2014; Gembler et al., 2014) and word selection system (Sanchez et al., 2011) have been the most common BCI applications.

The layout of the GUI plays an important role in creating a user-friendly and intuitive interface. Two crucial keys that need to be considered include the number of commands required for a selection and the arrangement of the light stimuli and the desired targets (Kick and Volosyak et al., 2014). Among the various layouts, grid layout (Friman et al., 2007; Volosyak et al., 2011) and decision tree layout (Cecotti et al., 2010; Vilic et al., 2013; See et al., 2013; Gembler et al., 2014) have been most commonly used for the speller GUI. The grid layout allows users to select one letter by one letter. On the other hand, the decision tree layout enables the content of the selected choice to be divided into a few choices. The speller with the decision tree layout thus provides higher character per minutes (CPM) and requires less number of commands for a selection (Akce et al., 2014). Therefore, the decision tree structure was adopted in the current BCI system design.

Some of the spellers were developed with a built-in dictionary (Volosyak et al., 2011; Villic et al., 2013). The dictionary in a speller can help to improve the spelling rate/ CPM (Volosyak et al., 2011; Villic et al., 2013). Normally, a dictionary of words was constructed to enable word completion in a speller. The word completion feature was originally developed for disabled people to decrease the number of keystrokes required to input words and sentences (MacArthur, 1996). It suggested one or more predictive words to users after the users input the initial letter of a word (Hunnicutt and Carlberger, 2001). In addition, recency (occurrence frequency of each word) was also incorporated in some of the dictionaries (Volosyak et al., 2011) to reduce the selection time as the frequently used words would appear first in the selection list. In the current study, the recency has been incorporated in the speller and word-based GUI selection system.

The GUI design in many of the previous studies required users to adapt to a few different layouts with different arrangements of light stimuli and desired targets (Volosyak et al., 2011; Villic et al., 2013). In the present study, the arrangement of light stimuli and desired targets was standardized throughout the applications to improve the user-friendliness of the system.

Most of the dictionaries used in the spellers are too general (Vilic et al., 2013; See et al., 2013; Volosyak, 2011). The large number of general words made the selection of the desired word slow. This problem was obvious in the Danish dictionary with over 164,000 words (Vilic et al., 2013). On the other hand, a dictionary for the word selection system (Sanchez et al., 2011) contains only eight words that were being used to answer some questions (words include "yes", "no", "good" and "bad") and express body situations (words include "heat", "pain", "cold" and "thirst"). Although this predefined set of words can provide quick communication between patient and physician, patients were usually unable to express themselves sufficiently.

In our study, the dictionary was constructed based on patient's needs for their daily living. The total number of words and pictures in the dictionary was limited to facilitate selections and to reduce the selection time.

2.6 Problems faced by the users

Although SSVEP-based BCIs worked with healthy users (Cheng et al., 2002; Guger et al., 2012b) and users with disabilities (Sutter et al., 1992; Wang et al., 2004; Müller et al., 2015), there is increasing evidence showing that it does not work for all users (Allison and Neuper, 2010). Some of the possible reasons include the inability of users to stay in focus, the unsuitable GUI and stimulation frequencies (Volosyak et al., 2009) as well as excessive muscle artifacts (Muller-Putz et al., 2005; Allison and Neuper, 2010). Patients could also demonstrate worse performance dynamics due to medications, visual deficits, partial brain damage, and neuropsychiatric conditions (Piccione et al., 2006; Ortner et al., 2011; Guger et al., 2012b; Schreuder et al., 2013).

The prevailing view in all the literature above is that there is no standard BCI system that works for all the users. The suggestion of BCI should adapt to each user's condition or requirement (Müller et al., 2015) is the essential key to improve the BCI performance. One of the adaptations made in this study is the customization of the word-based GUI for the user with high literacy level and the pictorial-based GUI for the user with low literacy level.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The design principle of the present SSVEP-based BCI system is described in this chapter. The system uses a light stimulus (LCD/ LED) flashing at specific frequencies to trigger SSVEP responses. The signals are collected, analyzed and translated into commands to control the BCI communication system. In order to investigate the functionality and workability of the developed system, it is first tested on healthy subjects. After some necessary modifications, the system is used on two patients with motor disabilities.

3.2 The present SSVEP-based BCI system

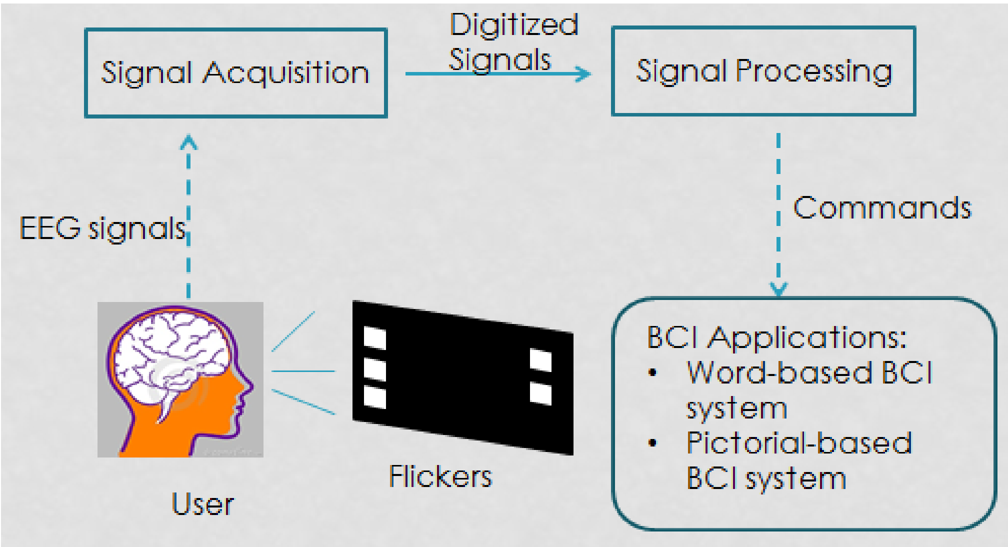


Figure 3.1: Functional model of the SSVEP-based BCI system.

Figure 3.1 shows the functional model of the present SSVEP-based BCI system. EEG signals were acquired through a standard EEG electrodes placed at the Oz position. The two–mastoids serve as reference (M1) and ground (M2) respectively. The placement of electrodes is illustrated in Figure 3.2.

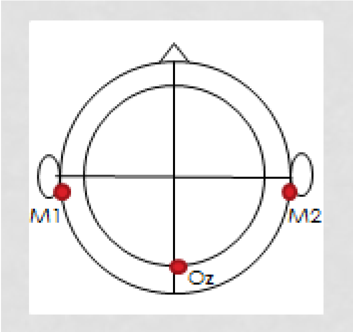


Figure 3.2: The placement of electrodes.

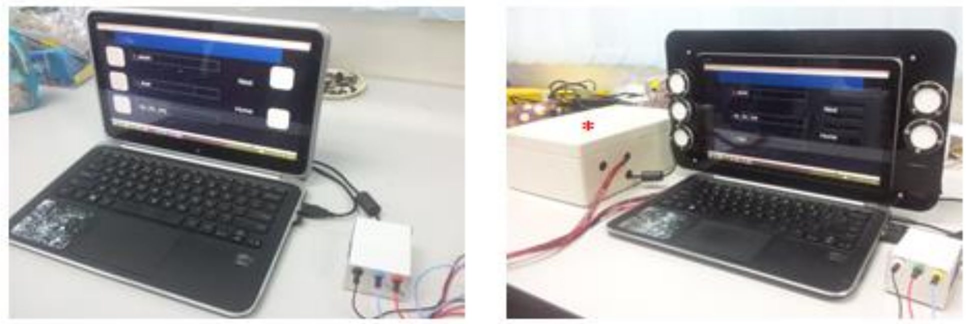
3.3 EEG acquisition

The signal acquisition was performed using the custom-made data acquisition module developed using a 24-bit Delta-Sigma ADC (Texas Instrument, ADS1299) that operates at 250 Hz with analogue front-end. The high precision and low noise characteristics of the analogue front-end make the acquisition of EEG signals possible with minimal extra components (Soundarapandian and Berarducci, 2010). A PIC24 microcontroller was selected to control the analogue front-end and to send the acquired signals to the laptop through a universal serial bus (USB) port. A band-pass finite impulse response digital filter with a pass band of 2 Hz to 23 Hz was implemented to filter the raw signals. Figure 3.3 shows the data acquisition module.

Figure 3.3: The data acquisition module. The green colored connector serves as the input of the signal channel, the yellow colored connector serves as the input of the reference channel and the white colored connector serves as the input of the ground channel.

3.4 Stimulators

Two types of stimulators were used in the present study – LCD and LED stimulators. The latter were custom fabricated from normal LEDs shielded in semi-transparent plastics, and were mounted on the two sides of the laptop using an aluminium frame. A PIC24 microcontroller was used to vary the frequencies of the LEDs. The construction of the LCD stimulators is simpler – flickering patches of light with different frequencies were generated and controlled using the DirectX software, eliminating the needs for dedicated hardware. To enhance the SSVEP responses, white stimuli and black background were used for both types of stimulators (Cao et al., 2014). Figure 3.4 depicts the BCI systems featuring the two different types of stimulators.



(a) (b)

Figure 3.4: BCI systems with two different stimulators. The small unit on the right of both pictures is the EEG acquisition module. (a) BCI systems with LCD stimulator. (b) BCI systems with LED stimulator. An extra piece of hardware (denoted by *) was required to control the flashing frequency of the led flicker.

3.5 Dictionary

3.5.1 Word-based GUI

The word-based GUI was designed with a phrase selection feature to reduce the number of necessary selections for user conversation. Instead of dealing with a comprehensive dictionary, the dictionary for phrase selection was customized to contain only a limited number of words (n = 156). These words were selected on the basis that they were commonly used by patients to express their needs for activities of daily living (Dr Saini, personal communication). The words were combined into phrases using “_” and built into sentences with simple grammar. Other than English, the dictionary was also made available in Chinese and Malay versions.

The words in the dictionary were categorized into three main groups, which are “I_want”, “I_feel” and “Do_for_me”. The first category was created for the users to express their feelings. For example, “I_feel happy”, “I_feel sad” and so on. The second category was created for the users to express their needs. For example, “I_want to_eat porridge”, “I_want to_drink water” and so on. The last category was created for the users to request for assistance. For example, “Do_for_me switch_on air_conditioner”, “Do_for_me switch_off fan”. (See APPENDIX A for the full content of the dictionary.)

All phrases in the dictionary (words combined by ‘_’ signs) were separately assigned to three of the selected stimulation frequencies, using a custom program developed in Visual C#. A “Next/ Clear” and a “Home/ Clear All” commands were made available with another two stimulation frequencies. The selected phrases were displayed on the top part of the screen. A screenshot of the GUI is shown in Figure 3.5.

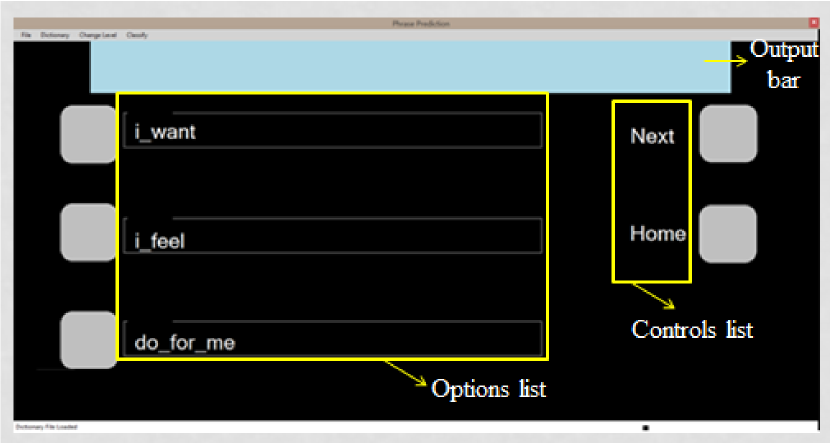


Figure 3.5: The screenshot of the layout design of the GUI of the phrase selection system.

The dictionary was constructed based on a non-linear tree structure. This was implemented by creating a text file that contained all the predefined sentences which was subsequently loaded into a program code. After that, the EXtensible Markup Language (XML) tree of phrase dictionary was generated (see Figure 3.6). Each node contained properties of previous word, current word, frequency (number of times the phrase appear in the dictionary), probability (total number of phrases divided by frequency), and recency. Lastly, an algorithm was executed to process the XML and extract the values in the node of “word” appeared on the option list.

```
<NewDataSet>
 <NodeTable>
  <Table>Table</Table>
  <Number>5</Number>
 </NodeTable>
 <Node0>
  <PrevWord />
  <Word>i_want</Word>
  <Freq>18</Freq>
  <Prob>0.31578947368421051</Prob>
  <Recency>6</Recency>
 </Node0>
```


Figure 3.6: Example of a segment of the generated XML tree of phrase dictionary.

In order to customize the content of the dictionary for a particular subject after several usages, two features were created. The first feature is recency. During the initial stage of using the system where the recency is zero, probability is used for the ranking of words in the option list. After several usages, the recency will take over. Each time a phrase is selected, the value of recency for that phrase will increase by one and the value is recorded in the XML file. For the subsequent selections, the phrase with the highest number of recency will appear on the top of the option list (See Figure 3.7). This effectively reduces the selection time for making repetitive/ similar sentences.

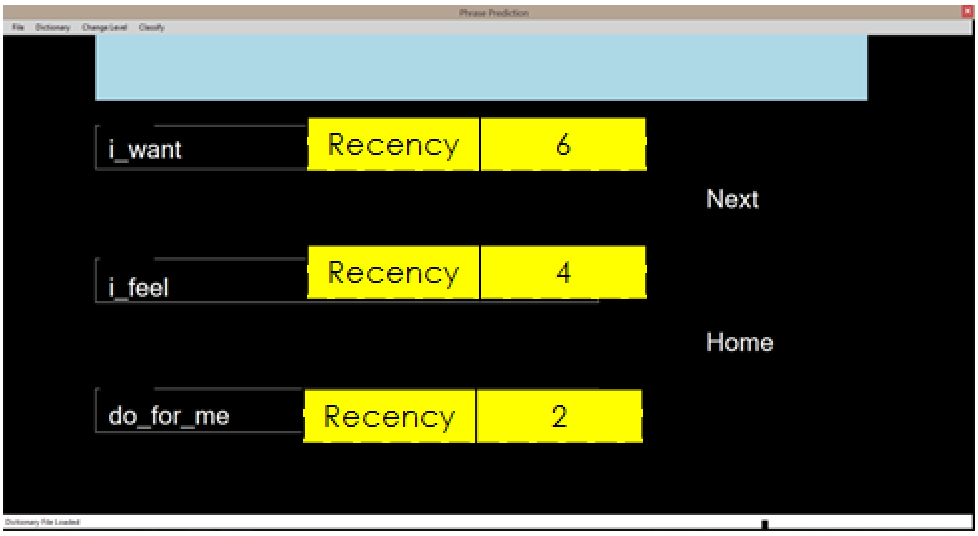


Figure 3.7: The phrases in the options list were displayed according to the recency in a descending order.

The second feature is the built-in speller which allows users to add new/ missing words into the existing dictionary. The speller consists of all 27 characters [A-Z#] and 6 punctuation marks. The symbol "#" represents options for 6 punctuation marks. In addition, the letter prediction system was integrated into the speller to reduce the selection time required. For example, to spell the character "A", the user needs three steps as shown in Figure 3.8 (From form #1 to form #3). After that, form #4 will be shown. The first row of the selection list contains characters from A to Z that enables the user to spell another new character. The second and third row of the selection list contains 6 predicted words according to the detected character shown in the blue label. If the expected phrase can't be found from the second and third row of the selection list, the user may select the first row list to navigate back to form #1. The "Clear all" command is used to erase all the selected characters on the blue label. The "Backspace" command is used to erase the last character on the blue label.

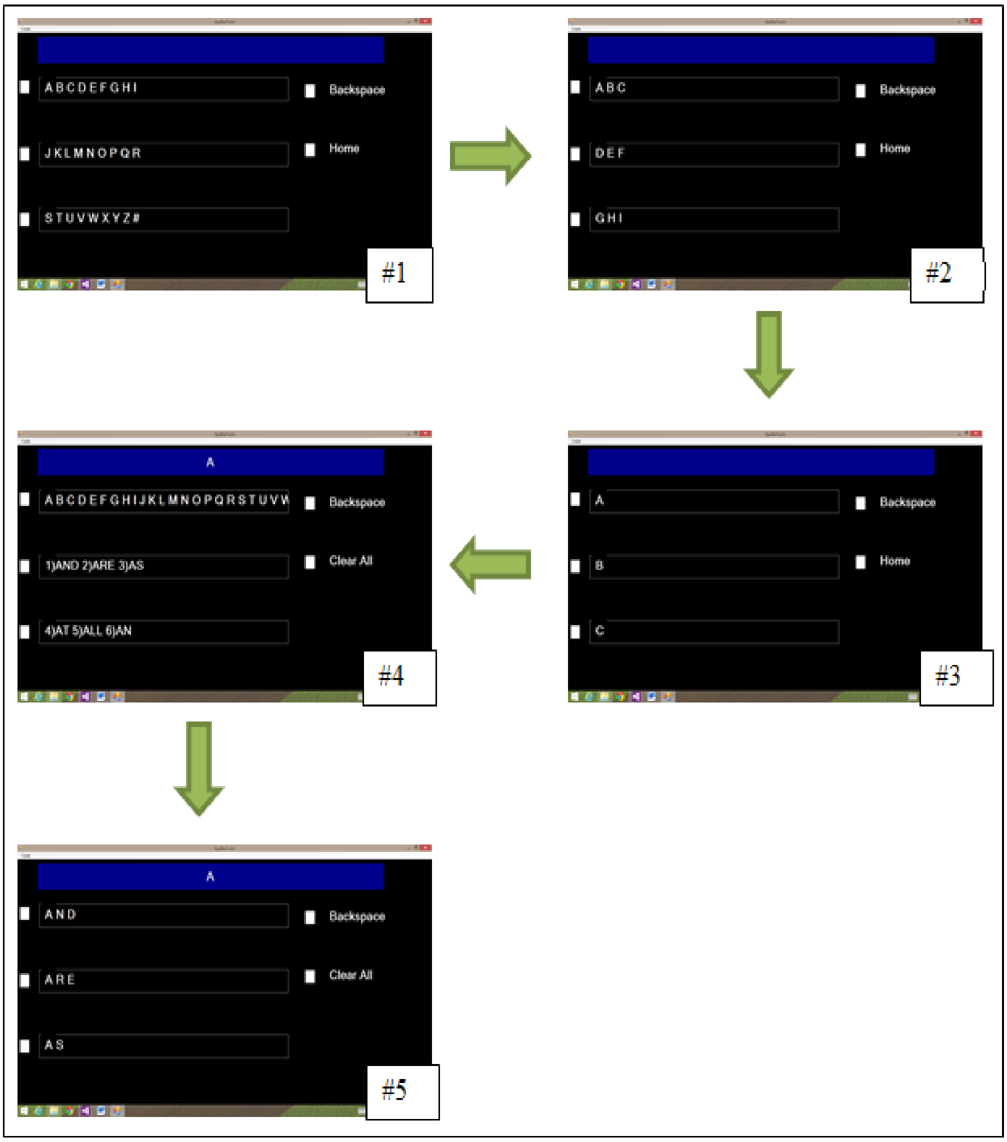


Figure 3.8: Screenshots of GUI of speller that present the flow of selecting "A".

The speller function which allows the user to spell one character at a time will only be shown if it is the last option in the phrase selection tree. As shown in the example in Figure 3.9, after the user selected “I want to eat”, three options -- “fruits”, “porridge” and “cereal” followed. If none of the options fit the user’s desire, he/ she can select the “Next” command to go the speller. The newly created word can then be added to the dictionary by selecting the "Yes" option in the confirmation form.

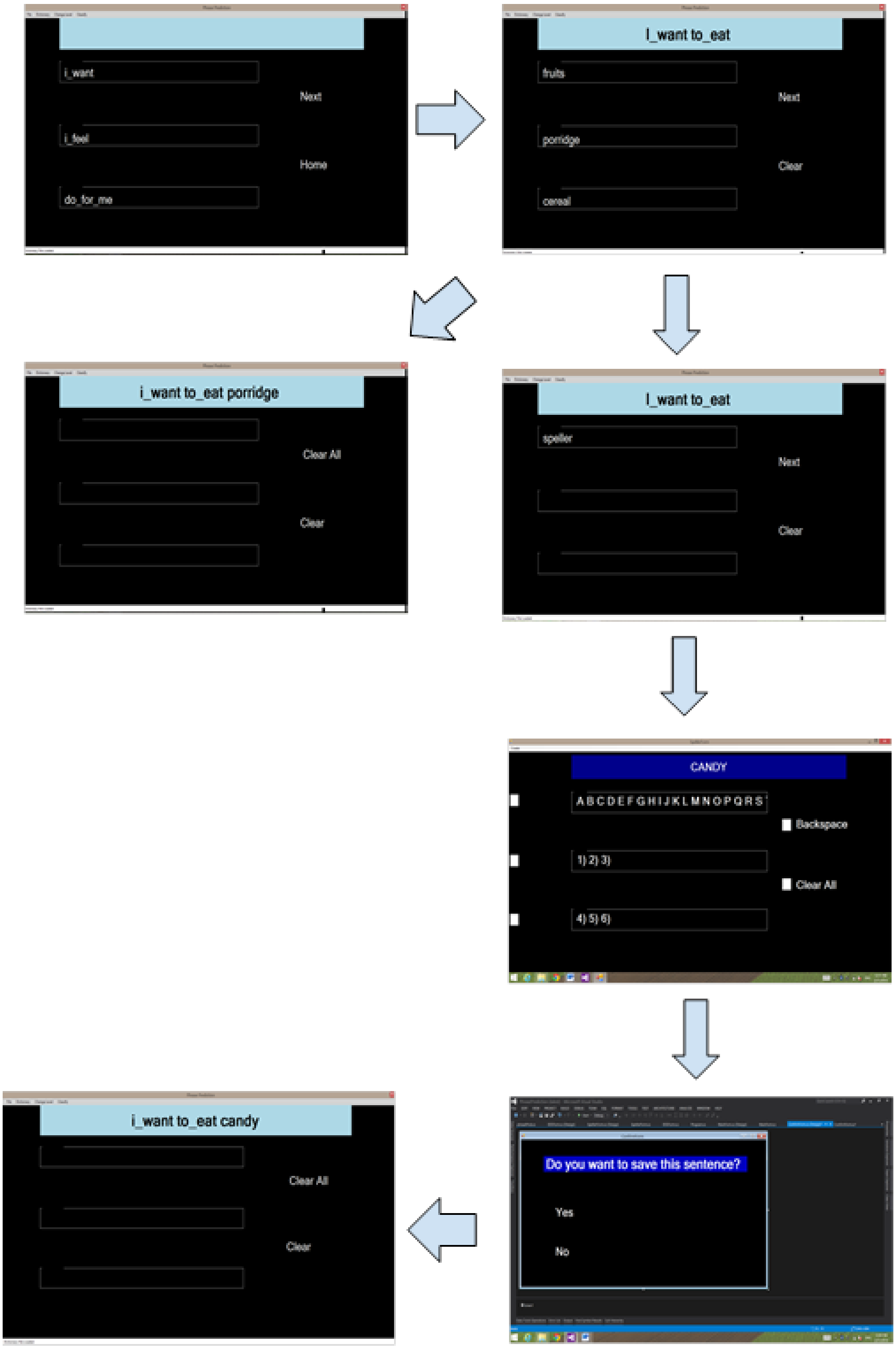


Figure 3.9: Screenshots of phrase selection system with integrated speller.

3.5.2 Pictorial-based GUI

The pictorial-based GUI was designed mainly for users with low literacy level. Users communicate by selecting pictures instead of phrases. There are altogether 102 pictures divided into six main categories featuring different aspects of the users' needs: cleanliness, food and drinks, entertainment, assistance, mobility, and feelings (See APPENDIX B for the full content of dictionary and APPENDIX C for all the screenshots of pictorial-based GUI). The content of the dictionary was custom designed for the user through an interview with the caregiver (see APPENDIX D).

Similar to the word-based GUI, the dictionary was built in a hierarchy tree structure. The six categories served as the parent node in the tree and subcategories served as child nodes. Those relevant pictures under categories or subcategories served as the leaf nodes. Some categories contain subcategories, which are food and drinks, entertainment and feelings. For example, there are 8 subcategories under the category of food and drinks (See Figure 3.10).

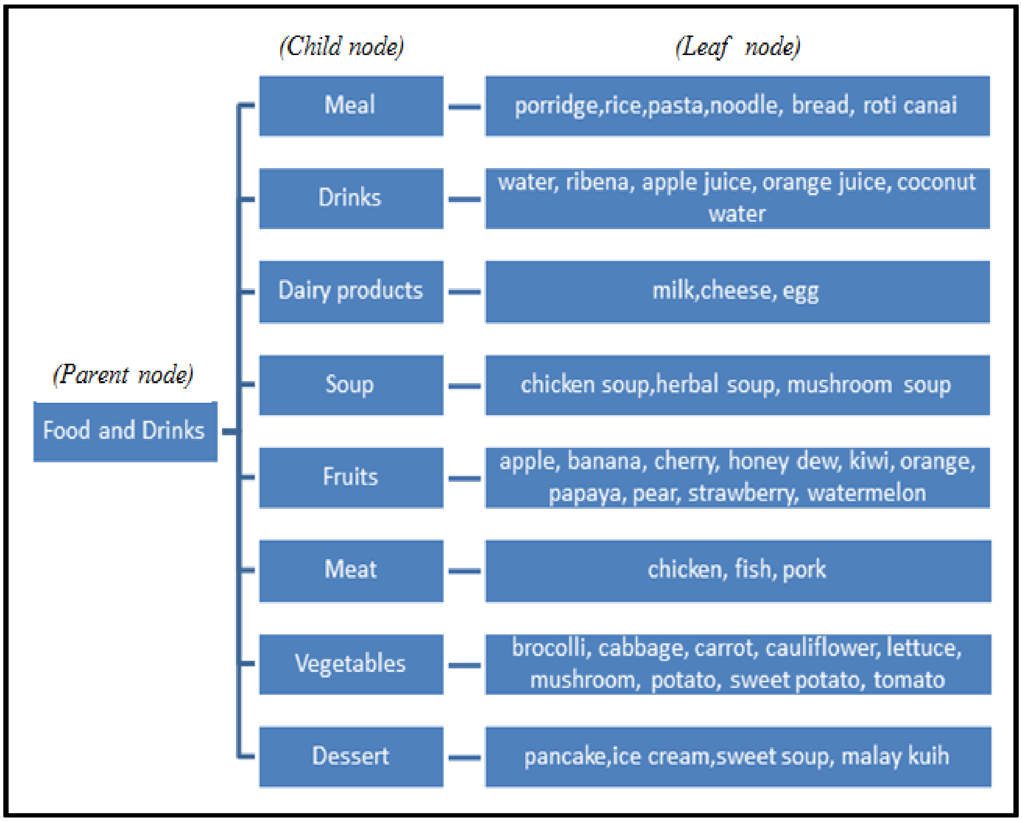
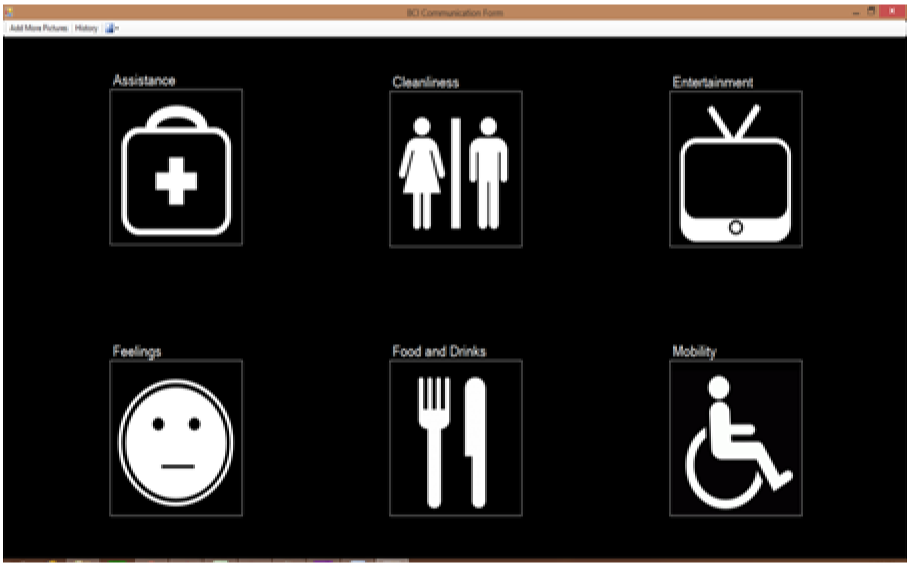
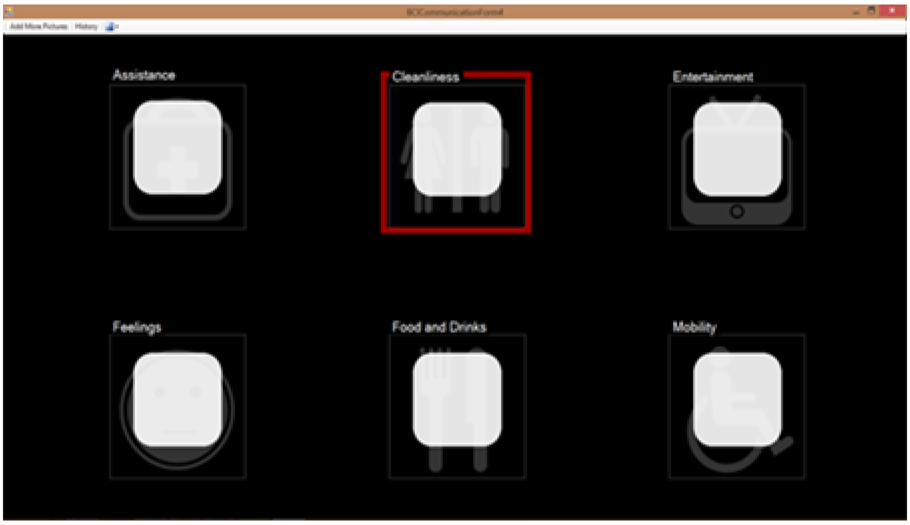


Figure 3.10: Hierarchy tree representation for “Food and Drinks”.

Since there are six categories in the dictionary, the layout of the GUI is equally divided into six parts. Each part contains a black and white symbol for group headings (parent node) (Figure 3.11(a)) and colored picture for the options (child node or leaf node) (Figure 3.12). Unlike the word-based GUI that displayed selected phrase in the output bar, sound feedback is implemented to read out the selected picture. To maximize the size of the selections and to avoid confusion of the users, the light patches are imposed on the pictures/ symbols.



(a)



(b)

Figure 3.11: Screenshot of the first page of pictorial selection (a) without flickers; (b) with flickers.

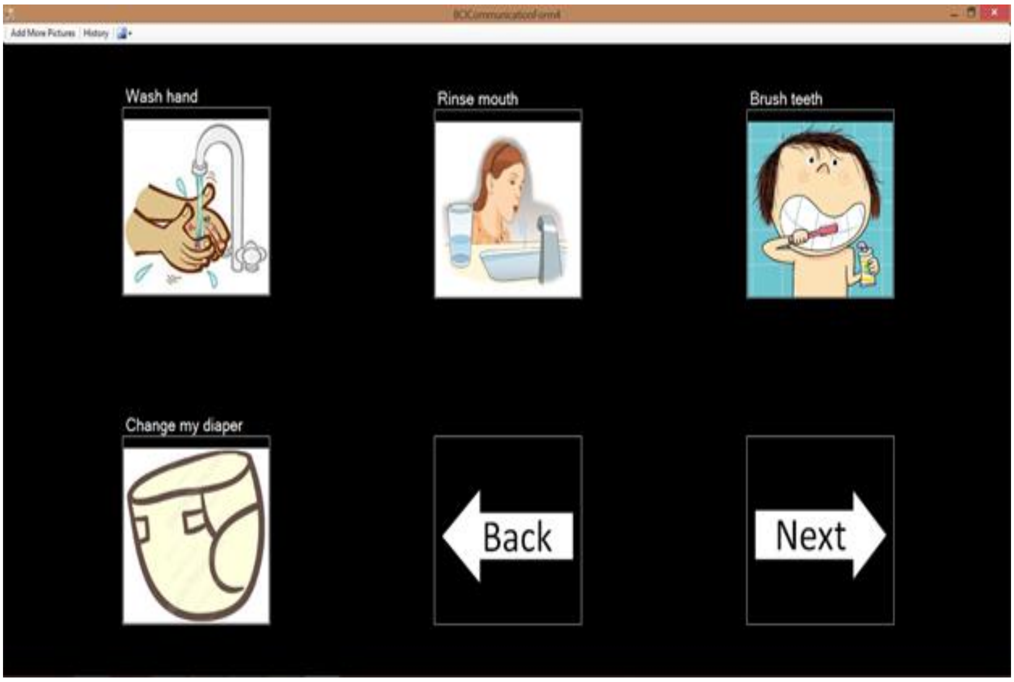


Figure 3.12: The screenshot of the related pictures shown after the group heading of "Cleanliness" was selected.

After a group heading is selected, four relevant selections together with the "Back" and "Next" options will prompt out. By clicking "Back", the system will navigate the user to the previous page. The system will navigate the user to the next page if "Next" is selected. Besides, caregivers are allowed to insert more selections/ pictures into the application by choosing the "add more pictures" option in the status bar on top of the window form. They can also remove the unwanted pictures by simply deleting them from the relevant folders (see Figure 3.13).

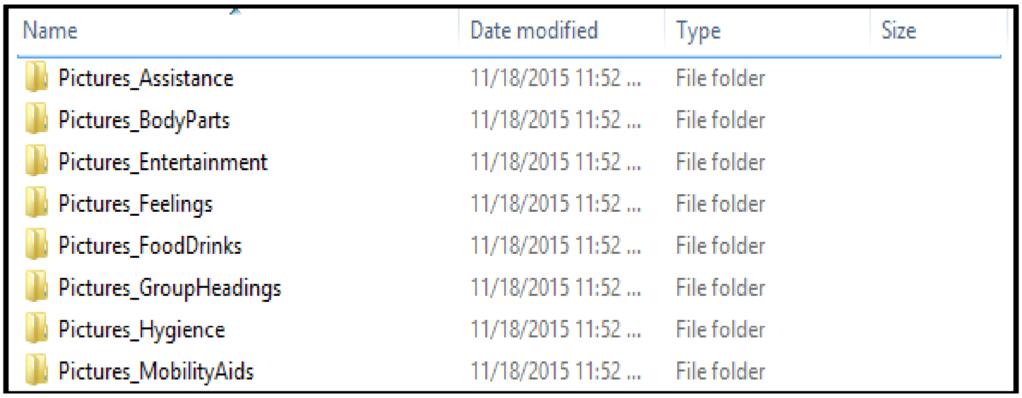


Figure 3.13: Folders to store relevant pictures.

3.6 BCI paradigm

The present BCI system is cue-based. In other words users can only make selections during the period of which the external cues are activated. From Figure 3.14, the black-colored box indicates the pre-cue time of which no selection can be made. During this period, there is no flickering to allow the user to rest. The white-colored box indicates the time of which the flickering started for users to make selections using brain signals.

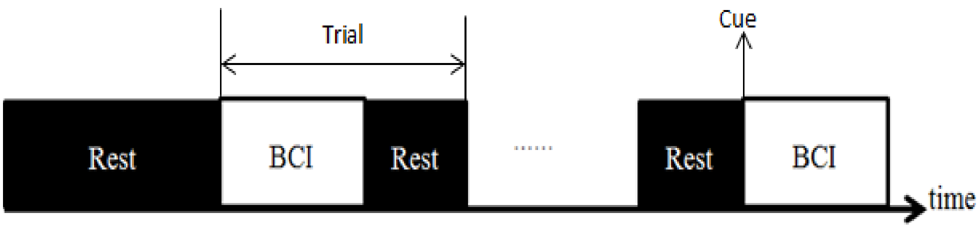


Figure 3.14: A cue-based BCI paradigm.

Depending on the tests, the duration for which the flickering is turned on varied from 10 s to 14 s. Rest period lasts between 5 s to 7 s. The exact paradigms for the different tests are detailed in Chapter 4.

3.7 Data analysis

3.7.1 SSVEP classification

The algorithm for classifying SSVEPs was adapted from Cheng et al. (2002). Briefly, a 1024-point Fast Fourier Transform (FFT) was performed every 0.1-second interval using the last 500 acquired data points (with 475 overlapped data points) padded with zeros. This is to improve the frequency resolution of the signals. The resulting amplitude of the FFT component that is the same frequency as the stimulus was taken as the feature for classification. SSVEP is classified when the signal-to-baseline ratio (SBR) of the particular frequency component is ≥2. Only SSVEP that persisted for six consecutive windows was classified as a successful selection.

SBR is defined as the SSVEP power of a particular frequency divided by the average SSVEP power of all stimulation frequencies. Trials contaminated by artifacts and those without noticeable SSVEPs were excluded from the analysis.

3.7.2 Accuracy and sensitivity

Accuracy and sensitivity are important performance measures for BCIs (Wolpaw et al., 2012). The classification accuracy and sensitivity are computed as below:

$$\text{Accuracy} = (TP + TN) / (TP + TN + FP + FN)$$

$$\text{Sensitivity} = TP / (TP+FN)$$

where TP, FP, TN and FN represent True Positive, False Positive, and True Negative, False Negative, respectively.

For the present system, no selection can be made when there is no flickering. Thus, TN is always equal to zero. Table 3.1 shows the possible outcomes of the present BCI system.

Table 3.1: Possible outcomes for the selection system.

Instruction		User's Response	
Make selection	Correct selection	Wrong selection	No selection
Classification	True Positive (TP)	False Positive (FP)	False Negative (FN)

CHAPTER 4

RESULTS

4.1 Word-based GUI

4.1.1 Classification performance of the healthy subjects

In total 12 healthy subjects were recruited in the study. They have normal or corrected to normal vision, no previous experience in BCI and no record of neurological disorders. Prior to the study, they were required to sign a consent form to indicate their voluntary participation (See APPENDIX E).

I_feel hot
Do_for_me switch_on air_conditioner
I_want to_go_to toilet
I_want to_drink fruit_juices
I_feel pain_in my_chest
Do_for_me call doctor

Figure 4.1: Six selected sentences as a required task to be completed.

The subjects were requested to select six sentences (Figure 4.1) in the performance test with five different stimulation frequencies (11, 12, 13, 14 and 15 Hz). If a selection was made in less than 14 seconds, the flickering would immediately stop. Else, the flickering would persist for a maximum of 14 seconds if no selection was made. After that, the flickering would stop for 7s to let subject to rest. In cases where a wrong selection was made, the subject had to “Clear” and to repeat the same attempts until the correct choice was finally selected. The classification accuracy was then calculated.

Figure 4.2 shows the classification accuracy of the subjects. The results show that only 66.7% subjects achieved ≥60% classification accuracy. This indicates that the standard set of stimulation frequencies does not suit those subjects who achieved lower classification accuracy. Therefore, pre-test was conducted on each patient to identify useful stimulation frequencies.

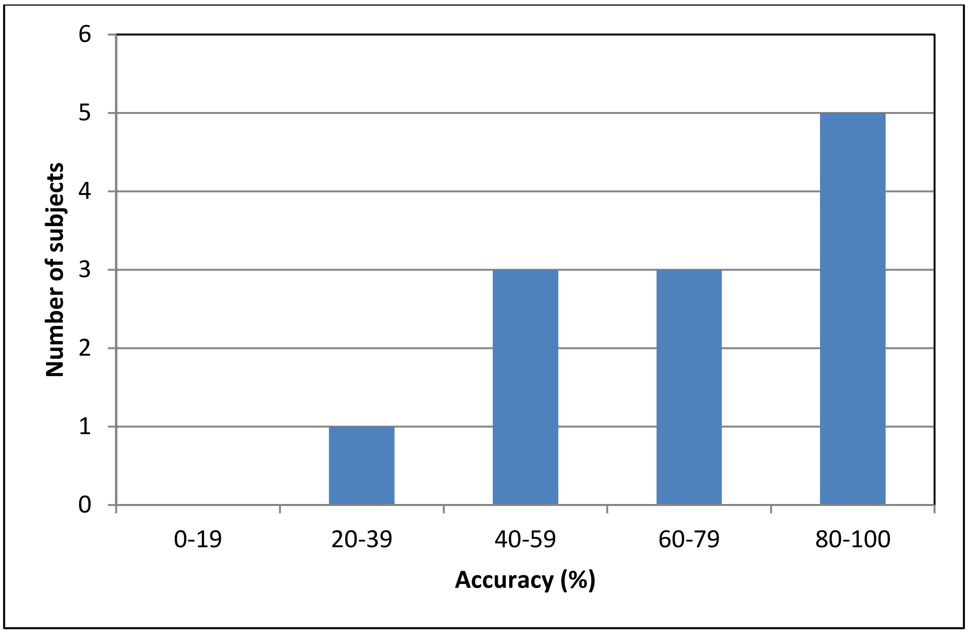


Figure 4.2: The accuracy distribution for word-based GUI selection system.

4.1.2 Classification performance of the patient

4.1.2.1 Case description

A 25-year-old male patient was recruited for this study. He was diagnosed with Duchenne Muscular Dystrophy (DMD) when he was six. He had difficulty in speech production, breathing and control over the joystick of the wheelchair However, he was able to use keyboards and mouse. The patient provided informed consent (APPENDIX E) to participate in the study.

4.1.2.2 Experiment paradigm of pre-test

A pre-test was performed on the patient to identify five optimum frequencies for BCI control. The test was first conducted using LCD stimulators, and later with LED stimulators.

LCD stimulators

The test consisted of five trials, one each for the following stimulation frequencies: 9, 11, 12, 13, and 14 Hz. For each trial, a single flickering square with the designated frequency was generated on the LCD screen. Each trial lasted for 17 seconds. From second 0 to 10, the square flickered and the patient was asked to focus on it. This was followed by a short break lasting 7 seconds. Subsequently, the next trial began. The entire test lasted about 2 minutes.

LED stimulators

The experimental paradigm applied was similar to that of the LCD stimulators. In detail, the test consisted of 15 trials. Each trial lasted for 21 seconds: 14 seconds of flickering and 7 seconds of break. A single LED was programmed to flicker at 16 Hz in the beginning of the test, and subsequently decrementing by 1 Hz after every three trials until 6 Hz. The entire experiment lasted about 6 minutes.

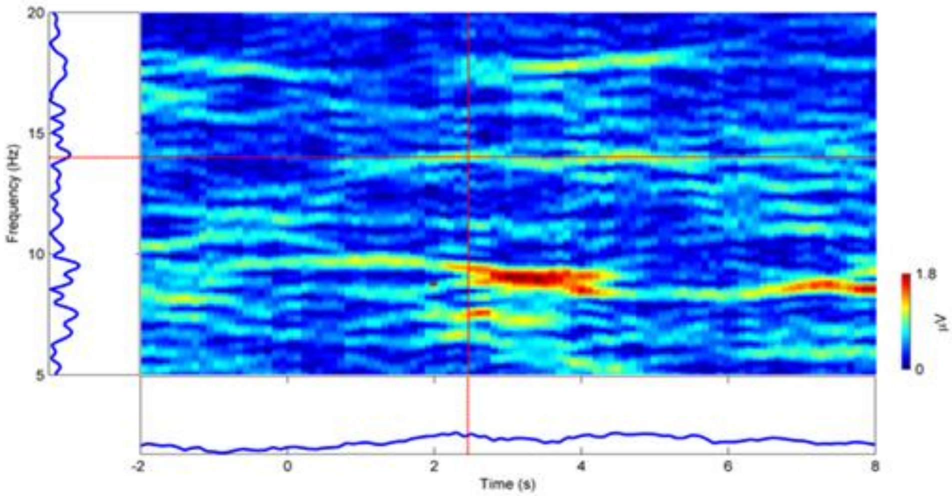
The EEG signals of the patient were acquired and analyzed for both experiments. Since only LED stimulators yielded five stimulation frequencies with useful SSVEP responses, LCD stimulators were dropped from the subsequent performance test.

4.1.2.3 Results of pre-test

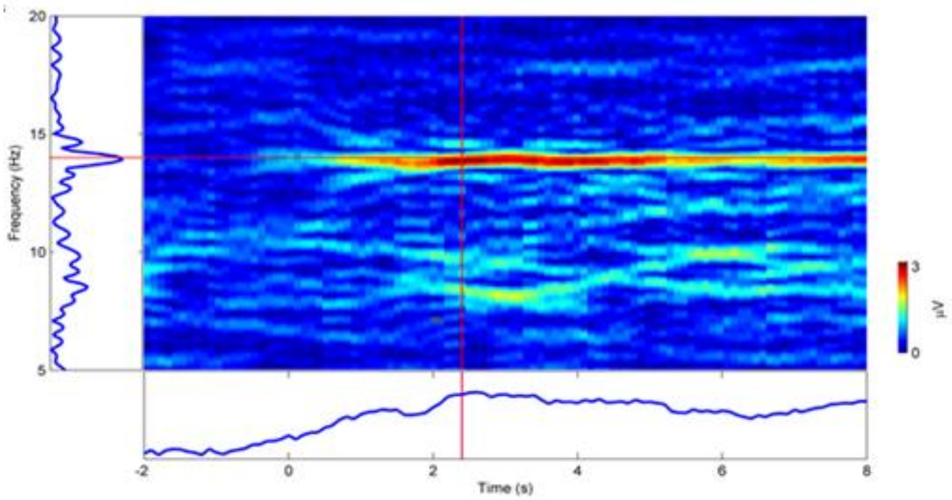
LCD Stimulators

Table 4.1: Signal-to-baseline ratio of SSVEPs evoked by LCD stimulators with different stimulation frequencies.

Frequency (Hz)	Signal-to-baseline ratio
9	9.03
11	6.07
12	7.58
13	3.31
14	6.50



(a)



(b)

Figure 4.3: Spectrogram of EEG signal in response to 14Hz stimulation during pre-test with LCD stimulators. (a) Patient's spectrogram of EEG signal. (b) Normal subject's spectrogram of EEG signal.

Table 4.1 shows the signal-to-baseline ratio of SSVEPs evoked by LCD stimulators with different stimulation frequencies. All tested stimulation frequencies produced SSVEPs that were well above the classification threshold. However, high-amplitude EEG signals were consistently recorded for the frequency band from 5 through 10 Hz across all trials, even during the break periods, as illustrated in Figure 4.3. A closer examination revealed that these signals were attributed to movement artifacts of the patient (the patient was jerking and moving most of the time) and an inherent alpha rhythm which predominate the EEG signals. Stimulation frequencies within this band, especially the 9 Hz that was used in this study, were therefore likely to hamper classifications of SSVEPs and lead to spurious detections.

Apart from that, the spectrogram of the patient's signals was exceptionally noisy (Figure 4.3). A clean spectrogram with a clear peak (Figure 4.3b) is especially useful in the classification of SSVEPs. However, not all the users exhibit spectrograms of the same features. In many cases, the spectrograms were of high background noise, and can easily trigger a wrong selection (Figure 4.3a). For this reason, LCD stimulators were dropped out from study.

LED stimulators

Table 4.2: Signal-to-baseline ratio of SSVEPs evoked by LED stimulators with different stimulation frequencies.

Frequency (Hz)	Signal-to-baseline ratio			
	Test 1	Test 2	Test 3	Mean $\pm$ S.D.
12	41.26	35.62	121.90	66.26 $\pm$ 48.27
13	19.47	74.34	30.60	41.47 $\pm$ 29.01
14	10.73	8.56	22.26	13.85 $\pm$ 7.36
15	21.93	58.38	29.12	36.48 $\pm$ 19.31
16	28.90	8.05	34.42	23.79 $\pm$ 13.91

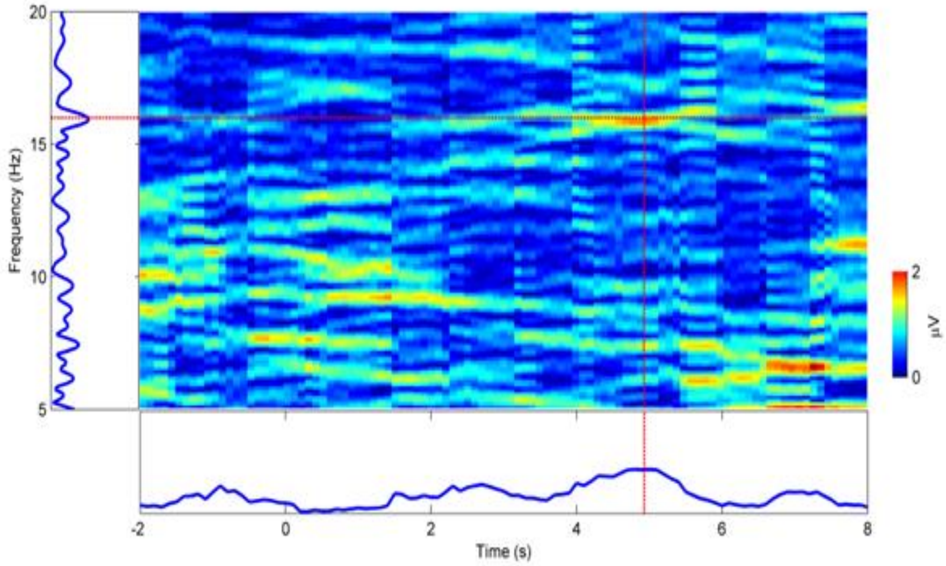


Figure 4.4: Spectrogram of EEG signals in response to 16Hz stimulation frequency during pre-test with LCD stimulators.

To remove the ambiguity in the recorded signals, the 9 Hz stimulation frequency was substituted by another frequency, 15 Hz during the pre-test with LED stimulators. The frequency adjacent to the alpha rhythm, 11 Hz was also replaced with 16 Hz. As shown in Table 4.2, 15 Hz and 16 Hz stimulation evoked potentially useful SSVEPs. The SSVEP amplitude for the other three frequencies were also of higher amplitude compared to those elicited by LCD stimulators, as expected. However, the frequency spectrum of the recorded signals remained noisy (Figure 4.4). A performance test was conducted on the patient with the five tested frequencies to assess the efficacy of the system.

4.1.2.4 Experiment paradigm of performance test

The patient was requested to select the six sentences as mentioned previously. If a selection was made in less than 14 seconds, the flickering would immediately stop. Else, the flickering would persist for a maximum of 14 seconds if no selection was made. After that, the flickering will stop for 7s to let patient to rest. In cases where a wrong selection was made, the patient has to "Clear" his selection and to repeat the same attempts until the correct phrase was finally selected. The classification accuracy was then calculated.

4.1.2.5 Results of performance test

Table 4.3: Classification results of the performance test.

	Number of selections
True Positive	33
True Negative	0
False Positive	13
False Negative	8
Accuracy	61.1%

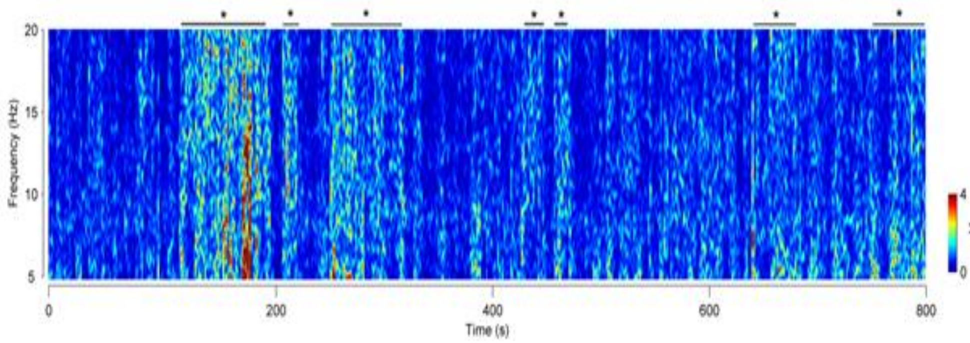


Figure 4.5: Spectrogram of EEG signals during performance test. The movement artifacts (denoted by *) of the patients that occurred throughout the whole test.

From the results shown in Table 4.3, the patient managed to achieve >60% classification accuracy, albeit his frequency spectrum was less well-organized than healthy subjects. However, the frequency spectrum of the EEG signals got increasingly messy as the test progresses (Figure 4.5), indicating that the patient was unable to concentrate over long periods.

4.2 Pictorial-based GUI

4.2.1 Classification performance of the healthy subjects

In total 43 healthy subjects were recruited in the study. They have normal or corrected to normal vision, no previous experience in BCI and no record of neurological disorders. Prior to the study, they were required to sign a consent form to indicate their voluntary participation (See APPENDIX E).

Table 4.4: Sets of pictures as required task to be completed.

Set 1	Set 2	Set 3
Assistance	Cleanliness	Food and drinks
Carry me	Change my diaper	Dairy products
Play with me	Next	Egg
Turn me	Pee	Milk
Back	Back	Back
Mobility	Brush teeth	Next
Bath chair	Back	Vegetables
Floor chair	Feelings	Cabbage
Pram	Itchy	Cauliflower
Wheelchair	Middle body parts	Next
Next	Arm	Lettuce
Back	Next	Potato

The subjects were requested to complete one set of pictures (Table 4.4) in the performance test. If a selection was made in less than 10 seconds, the flickering would immediately stop. Else, the flickering would persist for a maximum of 10 seconds if no selection was made. After that, the flickering will stop for 5s to let subject to rest. In cases where a wrong selection was made, the subject has to "Back" to previous page and to repeat the same attempts until the correct picture was finally selected. The classification accuracy was then calculated.

Figure 4.6 shows the classification accuracy of the subjects. The results indicate that only 53.5% subjects achieved ≥60% classification accuracy. This indicates that the standard set of stimulation frequencies does not suit to those subjects who achieved lower classification accuracy. Therefore, pre-test was conducted on patient to identify useful stimulation frequencies.

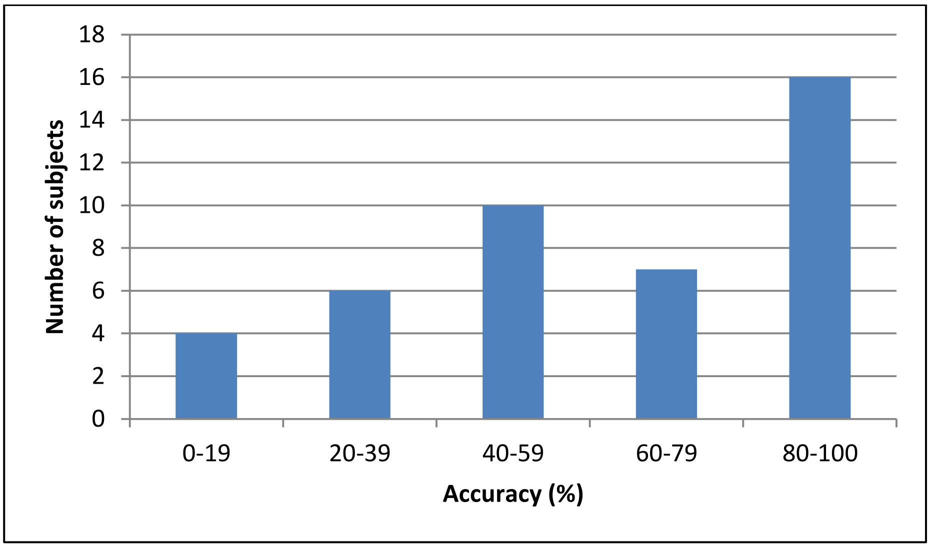


Figure 4.6: The accuracy distribution for pictorial-based GUI selection system.

4.2.2 Classification performance of the patient

4.2.2.1 Case description

A 4-year-old male patient was recruited in this study. He was diagnosed with Spinal Muscular Atrophy (SMA) during his age of one. He was able to write, paint and play IPad. Besides, he was able to sit with support and was cognitively alert to the surrounding. However, he had problem in pronouncing certain words or alphabets and he had developed progressive difficulty in delivering clear speech. The patient provided informed consent (APPENDIX E) to participate in the study.

4.2.2.2 Experiment paradigm of pre-test

A pre-test was performed on the patient to identify six optimum frequencies for BCI control. LCD stimulators were used for the test.

The test consisted of ten trials, one each for the following stimulation frequencies: 8.3, 11.23, 12.72, 12.21, 12.7, 13.18, 13.67, 14.16, 14.65 and 15.14 Hz. During each trial, a flickering square was rendered on the LCD screen for 10 seconds and the patient was asked to focus on it. This was followed by a short break lasting for 5 seconds. The entire test lasted for about 3 minutes. To keep the patient's attention, a feedback image of his favorite cartoon was shown with each correct attempt that he made and a feedback image of sad face was shown after each failed attempt (Figure 4.7).

Since the patient demonstrated satisfactory performance with the LCD stimulators, subsequent tests with LED stimulators were deemed not necessary.

Figure 4.7: Example of pictures which serve as feedbacks. Picture on the left side indicates wrong result made. Whereas, picture on the right side indicates correct result made. Different pictures are displayed for every trial.

4.2.2.3 Results of pre-test

The SBR of all the ten tested frequencies exceeded five (Table 4.5). Out of the ten frequencies, two failed to evoke SSVEP responses in one of the three trials. These two frequencies were dropped out from the subsequent tests. The six of the remaining eight frequencies with the highest SBR (14.65, 11.23, 12.7, 13.67, 12.21 and 8.3 Hz) (Figure 4.8) were selected for BCI control.

Table 4.5: Signal-to-baseline ratio of SSVEPs evoked by LCD stimulators with different stimulation frequencies.

Frequency (Hz)	Signal-to-baseline ratio			
	Test 1	Test 2	Test 3	Mean ±S.D.
8.3	15.96	12.33	8.93	12.40 ±3.51
11.23	14.58	21.69	20.26	18.84 ±3.76
11.72	26.21	19.06	-	22.64 ±5.05
12.21	10.39	14.3	24.24	16.31 ±7.14
12.7	12.69	24.97	19.22	18.96 ±6.15
13.18	9.77	9.5	-	9.63 ±0.19
13.67	16.8	26.12	7.8	16.91 ±9.16
14.16	14.16	8.01	9.9	10.69 ±3.15
14.65	14.57	31.24	11.27	19.03 ±10.71
15.14	14.78	11.8	10.59	12.39 ±2.16

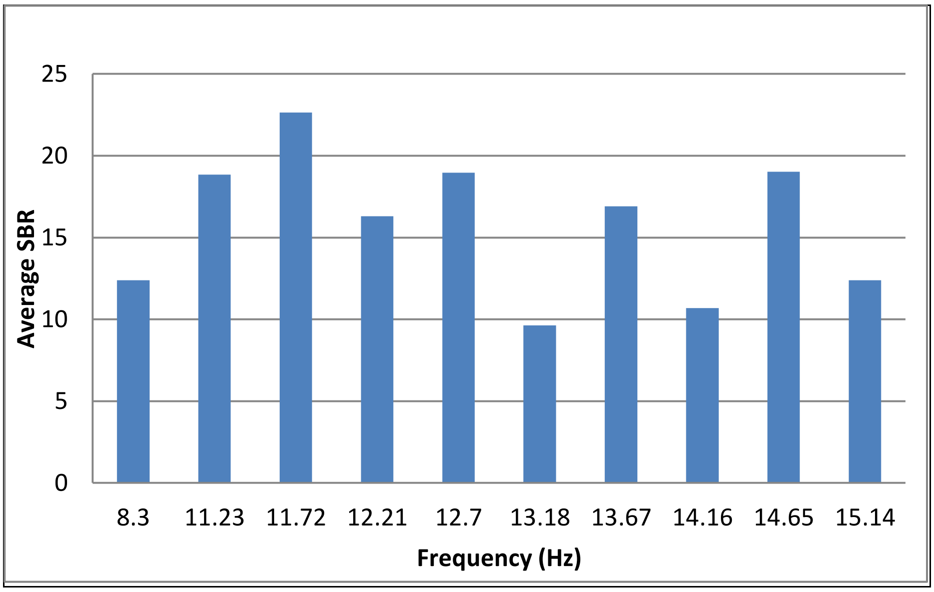
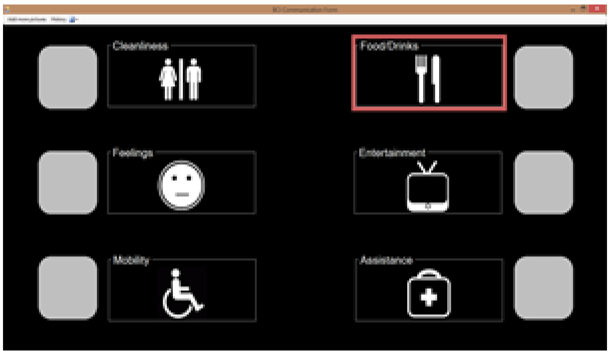


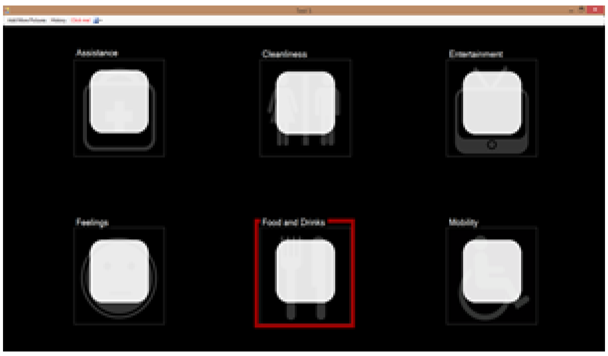
Figure 4.8: The average signal-to-baseline ratio for the 10 tested frequencies.

4.2.2.4 Performance test

All light patches were flickering simultaneously at different frequencies. The patient was expected to choose the picture that was indicated by the cue (colored rectangle). The test was conducted with two different versions of pictorial-based GUI. The first version features the flickering light patch side-by-side with the pictures (Figure 4.9a). In the second improved version, the light patch was imposed on the pictures to make the pictures larger and to avoid confusing the patient (Figure 4.9b).



(a)



(b)

Figure 4.9: GUIs of pictorial selection system. The colored rectangle serves as a cue indicator that indicates which picture the patient should focus in both GUIs. (a) First version of GUI. (b) Second version of GUI.

The patient was requested to complete a set of pictures as mentioned previously. If a selection was made in less than 10 seconds, the flickering would immediately stop. Else, the flickering would persist for a maximum of 10 seconds if no selection was made. After that, the flickering will stop for 5s to let patient to rest. In cases where a wrong selection was made, the patient has to “Back” to the previous page and to repeat the same attempts until the correct picture was finally selected. The classification accuracy was then calculated.

4.2.2.5 Result of performance test

Table 4.6: Classification result of the performance test by using first version of GUI.

	Number of selection				
	True positive	False positive	False Negative	Accuracy (%)	Sensitivity (%)
Test 1	5	4	3	41.7	62.5
Test 2	4	6	2	33.3	66.7
Test 3	3	5	4	25.0	42.9
Test 4	4	4	4	33.3	50.0

Table 4.7: Classification result of the performance test by using second version of GUI.

	Number of selection				
	True positive	False positive	False Negative	Accuracy (%)	Sensitivity (%)
Test 1	6	6	0	50.0	100.0
Test 2	5	7	0	41.7	100.0
Test 3	2	9	1	16.7	66.7
Test 4	8	4	0	66.7	100.0
Test 5	5	5	2	41.7	71.4
Test 6	3	7	2	25.0	60.0
Test 7	10	2	0	83.3	100.0
Test 8	7	4	1	58.3	87.5
Test 9	6	5	1	50.0	85.7

Table 4.6 shows the classification accuracy of the patient as well as the sensitivity of the BCI for the first version of GUI. The highest accuracy and sensitivity obtained was 41.7% and 66.7%, respectively.

The classification accuracy and sensitivity was improved with the second version of GUI (Table 4.7). The 9 tests were conducted on 3 different days: 1) Test 1, Test 2 and Test 3 were conducted on the first visit; 2) Test 4, Test 5 and Test 6 were conducted on the second visit; and 3) Test 7, Test 8 and Test 9 were conducted on the third visit. The accuracy was always the highest during the first tests and decreased drastically in the later tests, indicating that the patient was unable to focus over long periods. The patient managed to attain >80% accuracy in one of the tests. The classification accuracy for test 3 and test 6, however, was especially low (16.7% and 25.0%, respectively) as the subject did not focus on the flickering patches during the test (based on video recording). Apart from accuracy, the sensitivity of the BCI has also improved significantly reaching up to 100% with the second version of GUI.

CHAPTER 5

DISCUSSION

A high proportion of the healthy subjects (43.6%) attained unsatisfactory level of control (<60%) with the developed BCI system. A careful analysis revealed that this was mainly attributed to the standard set of stimulation frequencies used. Not all stimulation frequencies work for each individual and it is therefore important to carefully select the frequencies when designing the BCI system. In the present study, five/ six optimum frequencies were identified for the two patients through a pre-test that covered a range of stimulation frequencies. The five/ six selected SSVEP frequencies were randomly assigned to the five/ six choices in the GUI. A confirmation message would pop up every time after a selection was made. The patient may only proceed to the next selection after confirming the choices.

Since the results of the healthy subjects varied greatly, the various subject factors (age, gender, vision) were explored to find out if they have significant impact on the BCI performance. For the word-based GUI, the results showed that there was no significant correlation between age and BCI accuracy (Pearson Correlation analysis, $p = 0.302$). Independent t-test showed that there was no significant difference in the BCI accuracy between subjects with corrected vision ($N = 9$; $M(SD) = 72.23(28.56)\%$) and subjects with good vision ($N = 3$; $M(SD) = 71.17(12.52)\%$), $t(10) = 0.061$, $p = 0.952$). There was also no significant difference in the BCI accuracy between female subjects (N = 6; M(SD) =72.22(31.48)%) and male subjects (N = 6; M(SD) = 71.72(19.42)%), t(10) = 0.033, p=0.974. For the pictorial-based GUI, the results showed that there was no significant correlation between age and BCI accuracy (Pearson Correlation analysis, p = 0.526). Independent t-test showed that there was no significant difference in the BCI accuracy between subjects with corrected vision (N = 30; M(SD) = 65.48(5.33)%) and subjects with good vision (N = 13; M(SD) = 56.92(24.06)%), t(41) = 0.928, p = 0.952). There was a significant difference in the BCI accuracy between female subjects (N = 17; M(SD) =73.42(24.97)%) and male subjects (N = 26; M(SD) = 56.01(27.74)%), t(41) = 2.092, p=0.043. A more conclusive result of the impact of different subject factors on the BCI performance, however, can only be made by testing the BCIs over a larger number of subjects.

One of the remarkable features of the DMD patient that made him unable to use the BCI system with LCD stimulators was his inherently "active" alpha rhythm. The 9 Hz frequency component was too dominant and it manifested itself regularly in the EEG spectrums even when the patient was focusing on other stimulation frequencies. This would certainly compromise the classification accuracy. Notably, this is not a unique case; Müller-Putz et al. (2005) reported a similar phenomenon in a healthy subject recruited for their study. While it appeared to be straightforward to surmount the problem by replacing the 9 Hz stimulus with another one, the number of available frequencies was limited. On the lower end of the spectrum (5-10 Hz), activation signals were consistently detected presumably due to the uncontrollable jerking movements of the patient. On the higher end (>14 Hz), uniform luminance was compromised by the refresh rate of the LCD monitor (60 Hz in this case). Another possible alternative was to go for intermittent frequencies, but they were likely to add to the ambiguity of the detected signals due to the unusually high noise level in the EEG spectrums of the patient. The solution was to use LED stimulators, which enabled the patient to obtain an acceptable level (≥60%) of BCI control. Further improvements were to be pursued but unfortunately the patient passed away in the midst of the intervention period.

The 4-year-old SMA patient, on the other hand, showed good SSVEPs with high amplitude signals and clean EEG spectrums when tested with LCD stimulators. This rendered the use of LED stimulators unnecessary. Challenges remained, however, as the patient has low literacy level and was unable to use the word-based BCI system. More importantly, the patient lost his focus easily. To overcome the problems, a pictorial-based BCI system was custom developed for the patient. Feedback images of his favorite cartoon characters were also added to keep his attention throughout the tests. This later paradigm has been successful in retaining the patient's interest and focus at the beginning of the tests. Yet, his focus was compromised after an extended period of time, shown by the drastic drop in the accuracy in the later tests compared to the earlier tests. To improve the consistency, it is suggested for the patient to learn to regulate and strengthen his mental states through mental training (Tan et al., 2014; Tan et al., 2015).

The current outcome from the above two case studies was encouraging, as it showed that more users who were once thought to be BCI illiterate could benefit from a working BCI system that is adapted to match their abilities. This is particularly important in actual clinical settings where patients may experience altered performance dynamics and therefore standard BCIs are not readily suited for their use (Allison and Neuper, 2010). The end result of these adaptations is a customized communication tool that helps patients to communicate with the external world to improve their quality of life.

CHAPTER 6

CONCLUSION

6.1 Conclusion

A SSVEP-based BCI system was developed in the present study. There are two types of GUIs used – one using words and the other using pictorial representations for selections. Both allowed the patients acceptable levels of BCI control after certain adaptations. In the first case study, the BCI system was modified to be used with the LED stimulators as the LCD stimulators failed to trigger useful SSVEP responses. Besides, optimum stimulation frequencies were chosen through a pre-test before being incorporated into the system to improve the level of BCI control. For the second case study, a pictorial-based GUI was custom developed for a 4-year-old patient with low literacy level. Sound feedback was implemented to read out the selected pictures. To further increase the patient's interest, feedback images of his favorite cartoon characters were displayed after each trial. In both cases, the content of the dictionary was custom designed based on the needs of the patient.

6.2 Future work

A few system parameters including the stimulation frequencies and types of electrodes could be further optimized to improve the BCI performance.

The system processing algorithm can be modified to allow for detection of high-frequency SSVEPs (>20 Hz). The number of false positive selection is expected to be reduced as stimuli in this higher range are known to produce lower background noise (Wang et al., 2005). Additionally, high-frequency stimuli also hold the promise of reducing visual fatigue, which would in turn minimize signal degradation and enhance BCI performance (Wang et al., 2005; Diez et al., 2011).

Finally, dry electrode that does not rely on the use of electrolytic gel should be considered to reduce sensitivity to motion artifacts and to improve the users' comfort.

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APPENDIX A

DICTIONARY'S CONTENTS FOR WORD-BASED BCI SYSTEM

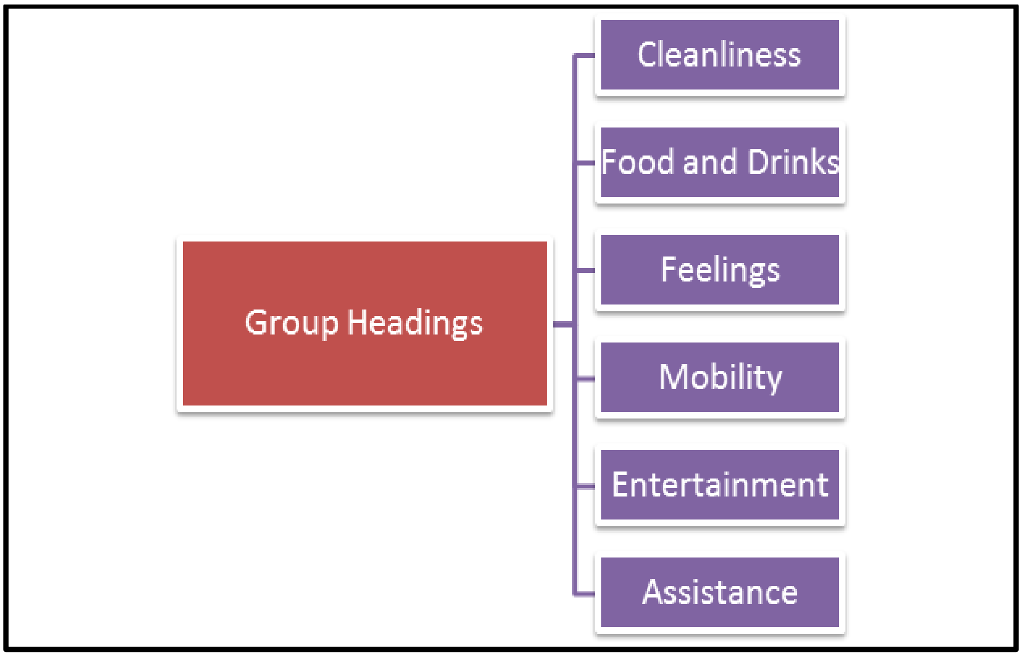
(ENGLISH)

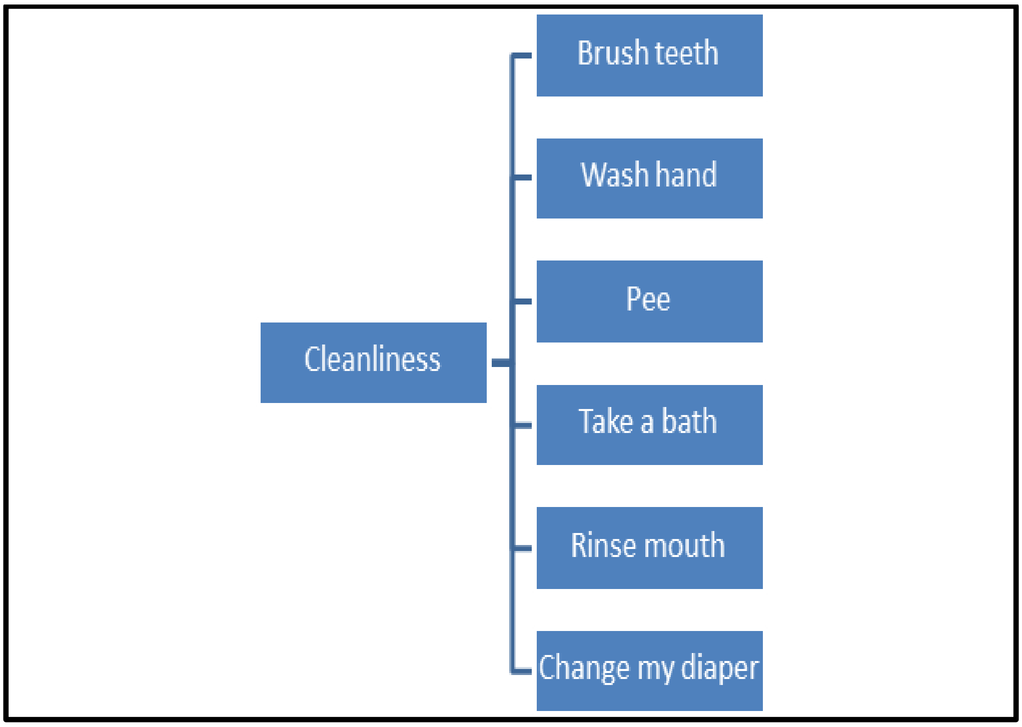
I_want to_eat fruits	I_want to_wash speller
I_want to_eat porridge	I_want to_go_to toilet
I_want to_eat cereal	I_want to_go_to garden
I_want to_eat speller	I_want to_go_to bedroom
I_want to_drink water	I_want to_go_to speller
I_want to_drink fruit_juices	I_want to_sleep now
I_want to_drink speller	I_want to_sleep later
I_want to_watch movie	I_want to_sleep speller
I_want to_watch news_channel	I_want speller
I_want to_watch speller	I_feel hot
I_want to_listen_to music	I_feel cold
I_want to_listen_to radio	I_feel hungry
I_want to_listen_to speller	I_feel thirsty
I_want to_wash my_face	I_feel tired
I_want to_wash my_body	I_feel uncomfortable
I_want to_wash my_leg	I_feel pain_in my_right_shoulder
I_want to_wash my_hands	I_feel pain_in my_left_shoulder
I_want to_wash my_hair	I_feel pain_in my_both_shoulders
I_feel pain_in my_chest	Do_for_me change my_bedsheet
I_feel pain_in my_back	Do_for_me change the_tv_channel
I_feel pain_in my_neck	Do_for_me change tv_to news_channe
I_feel sad	Do_for_me change speller
I_feel speller	Do_for_me call doctor
Do_for_me switch_on air-conditioner	Do_for_me call my_family
Do_for_me switch_on fan	Do_for_me call nurse
Do_for_me switch_on light	Do_for_me call ambulance

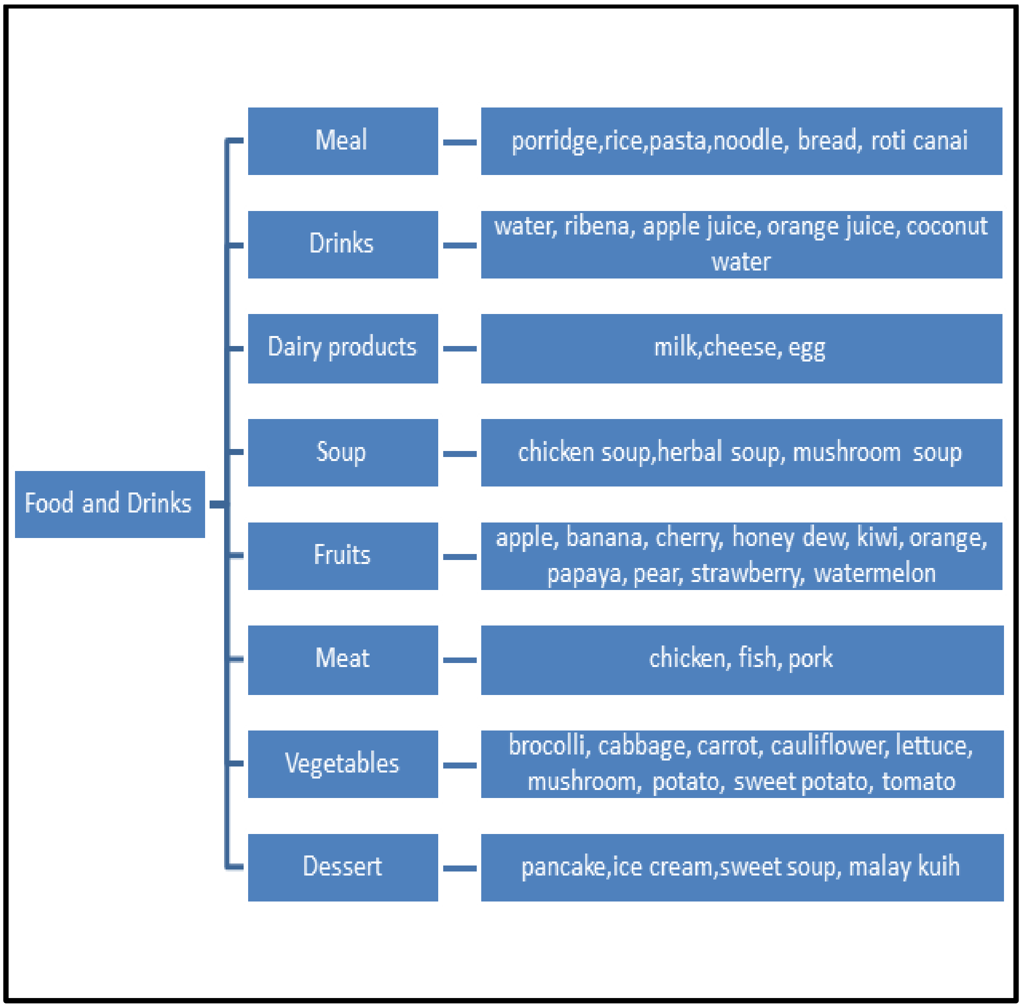
Do_for_me switch_on speller	Do_for_me call Speller
Do_for_me switch_off air-conditione	Do_for_me close the_door
Do_for_me switch_off fan	Do_for_me close the_window
Do_for_me switch_off light	Do_for_me close speller
Do_for_me switch_off speller	Do_for_me open the_door
Do_for_me switch_on music louder	Do_for_me open the_window
Do_for_me switch_on music softer	Do_for_me open speller
Do_for_me switch_on tv louder	Do_for_me speller
Do_for_me switch_on tv softer	
Do_for_me change my_diaper	
Do_for_me change my_clothes	

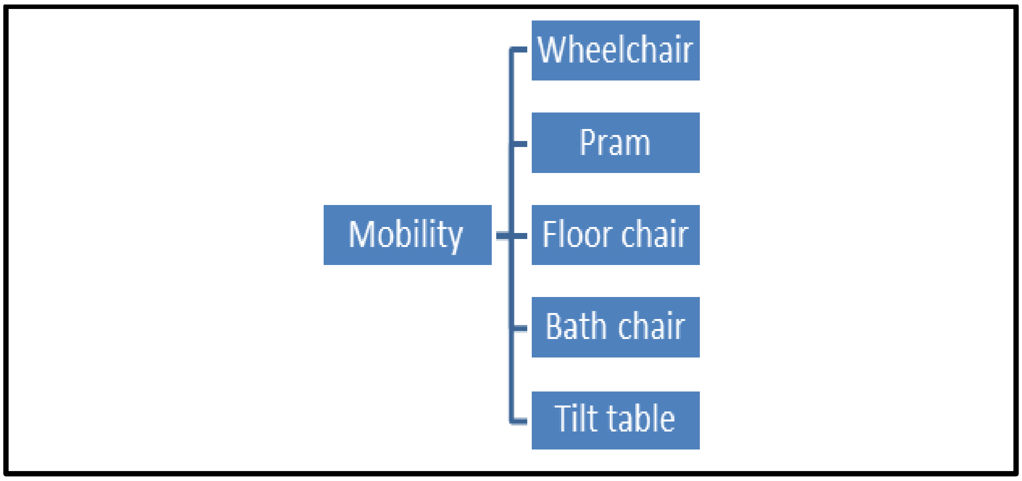
APPENDIX B

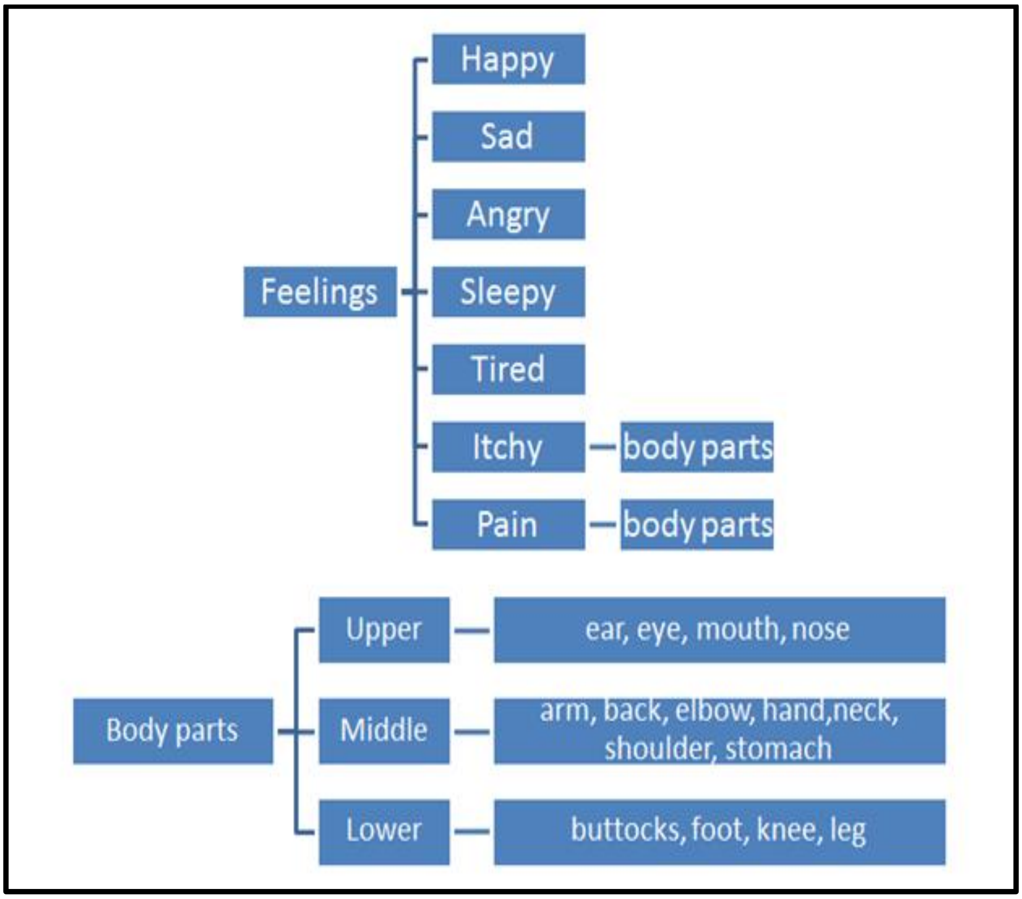
DICTIONARY'S CONTENTS FOR PICTORIAL-BASED BCI SYSTEM

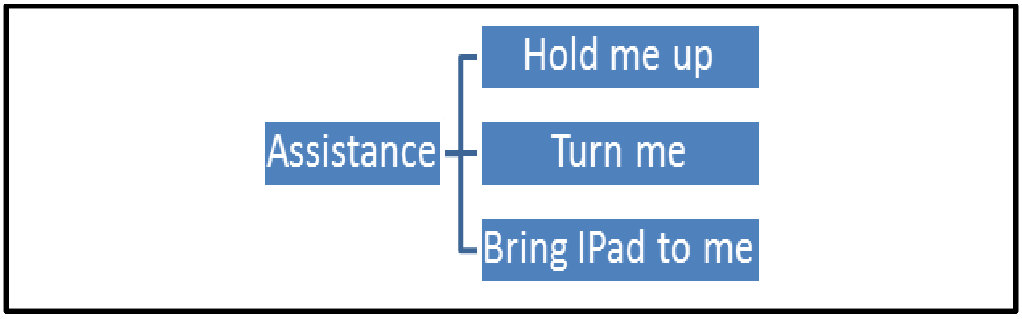


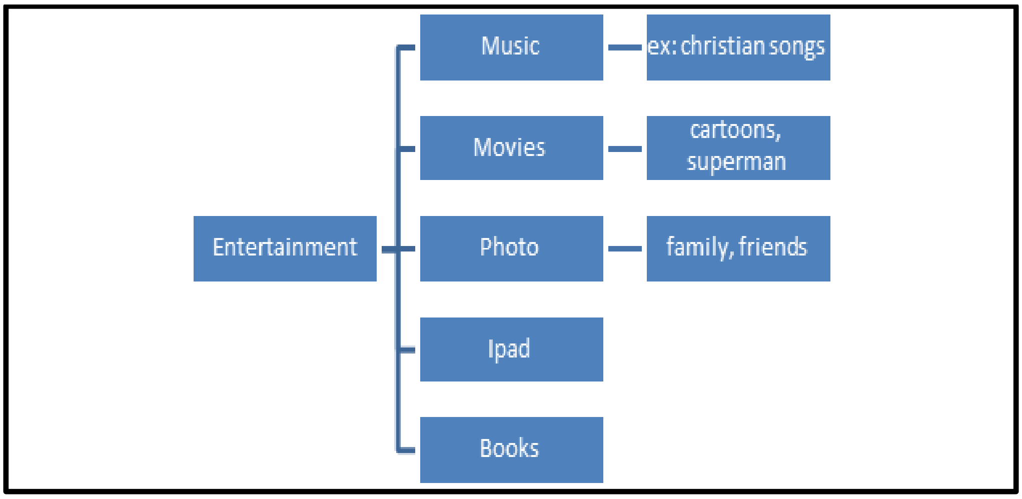



Food and Drinks
Meal
porridge,rice,pasta,noodle, bread, roti canai
Drinks
water, ribena, apple juice, orange juice, coconut water
Dairy products
milk,cheese, egg
Soup
chicken soup,herbal soup, mushroom soup
Fruits
apple, banana, cherry, honey dew, kiwi, orange, papaya, pear, strawberry, watermelon
Meat
chicken, fish, pork
Vegetables
brocolli, cabbage, carrot, cauliflower, lettuce, mushroom, potato, sweet potato, tomato
Dessert
pancake,ice cream,sweet soup, malay kuih


Mobility
Wheelchair
Pram
Floor chair
Bath chair
Tilt table


Feelings
Happy
Sad
Angry
Sleepy
Tired
Itchy
body parts
Pain
body parts
Body parts
Upper
ear, eye, mouth, nose
Middle
arm, back, elbow, hand,neck, shoulder, stomach
Lower
buttocks, foot, knee, leg


Assistance
Hold me up
Turn me
Bring IPad to me


Entertainment
Music
ex: christian songs
Movies
cartoons, superman
Photo
family, friends
Ipad
Books

APPENDIX C

SCREENSHOTS OF PICTORIAL SELECTION'S GUI

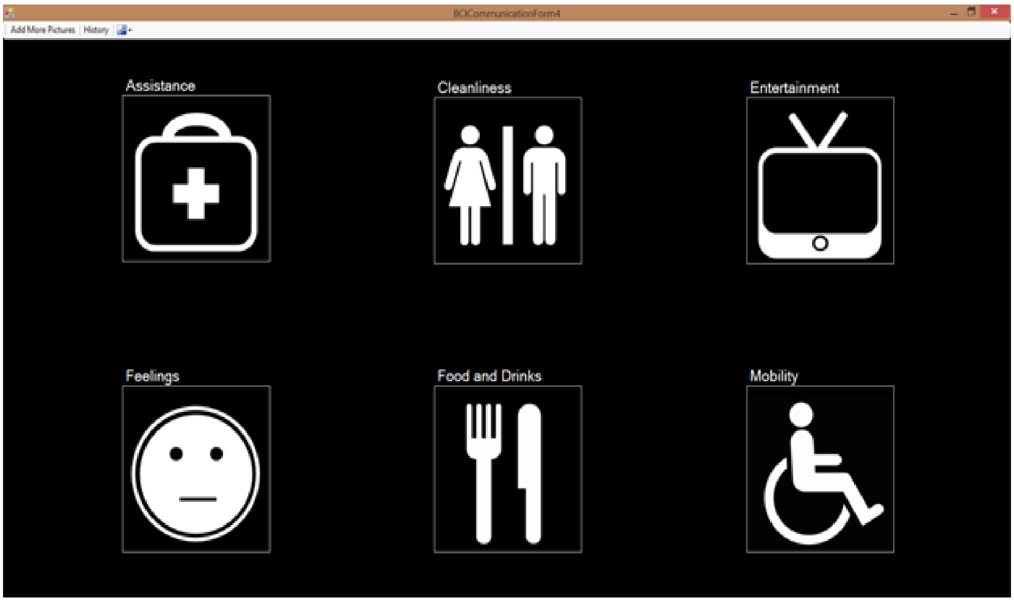


Figure 1: The screenshot showed six main group headings of pictorial selection.

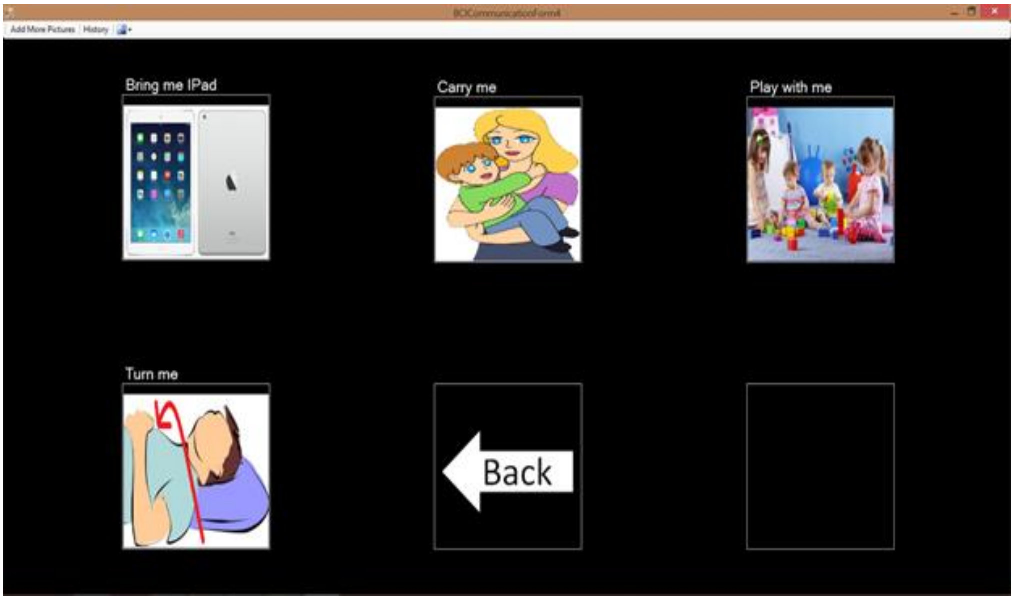


Figure 2: The screenshot showed the options for group heading of "Assistance".

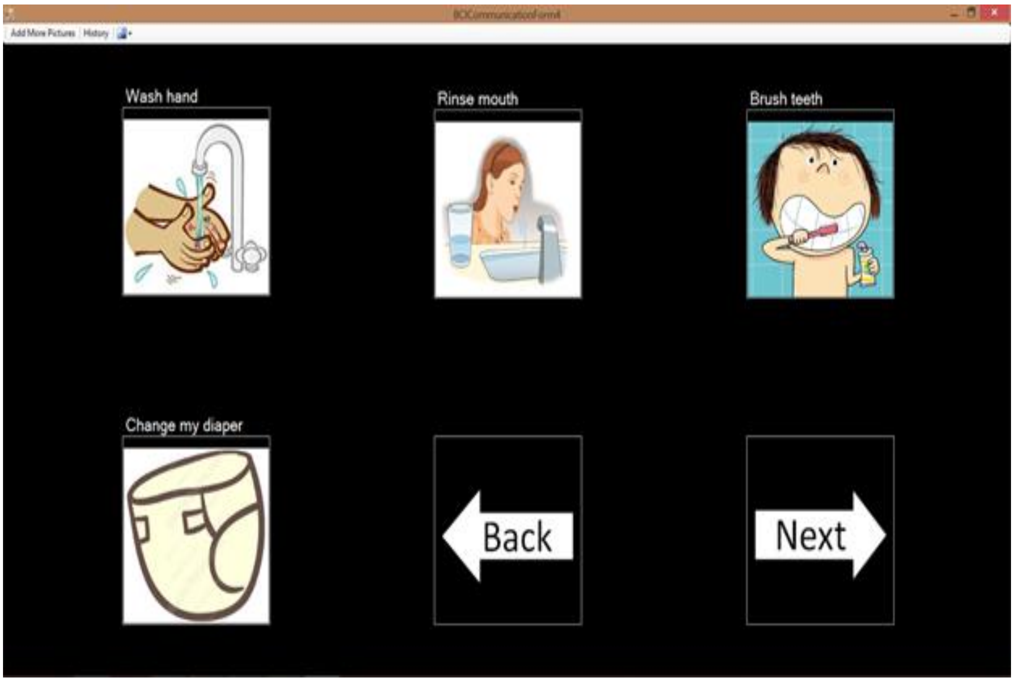


Figure 3: The screenshot showed the options for group heading of "Cleanliness" (layout 1).

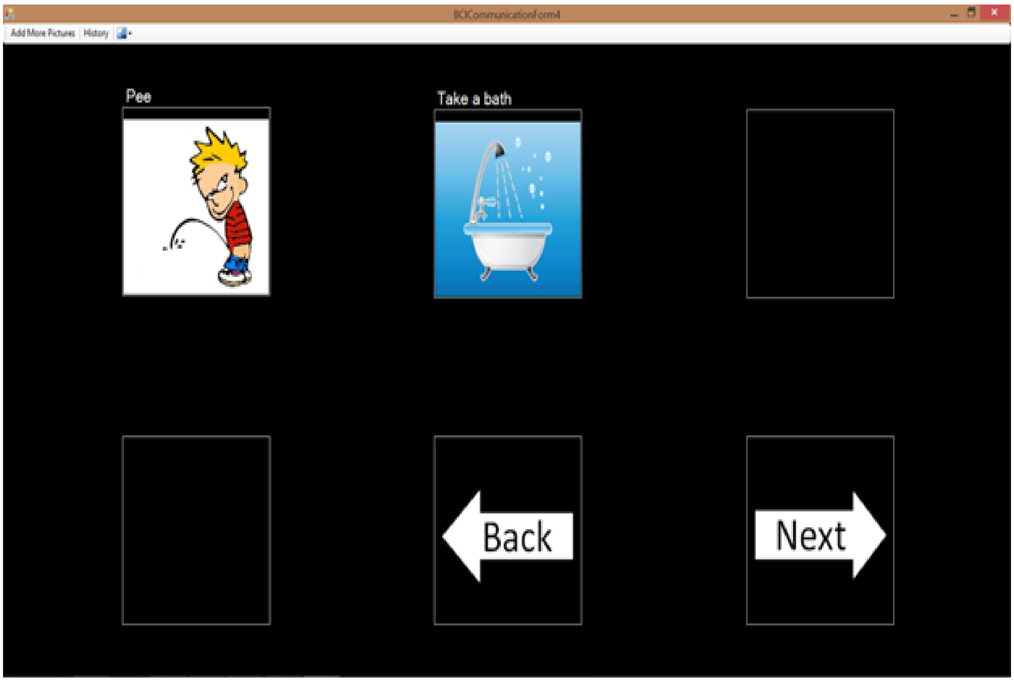


Figure 4: The screenshot showed the options for group heading of "Cleanliness" (layout 2).

Figure 5: The screenshot showed the options for group heading of “Entertainment” (layout 1).

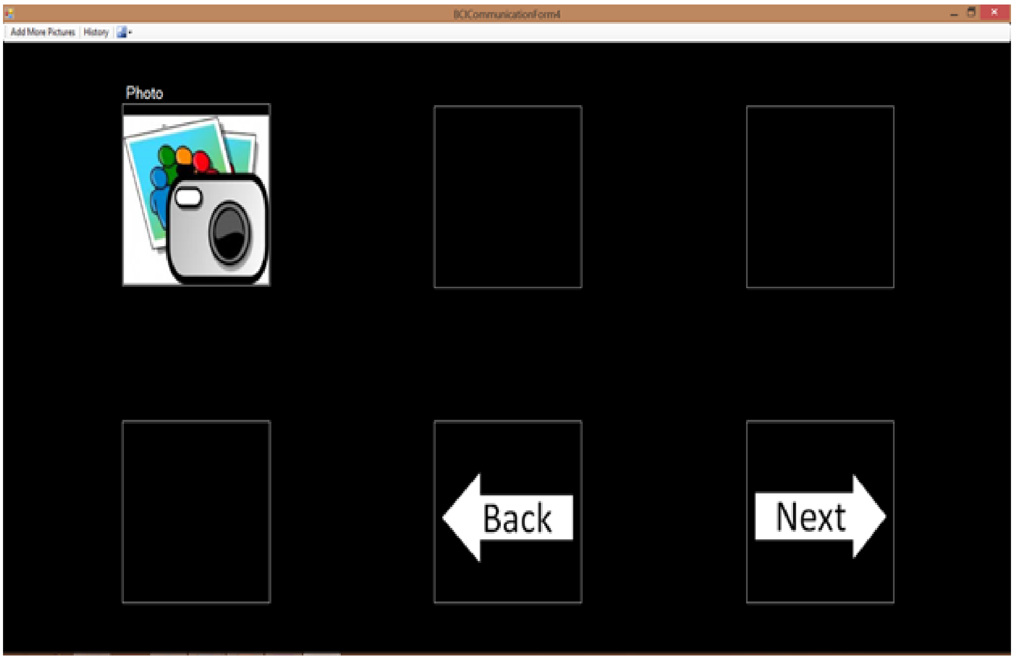


Figure 6: The screenshot showed the options for group heading of “Entertainment” (layout 2).

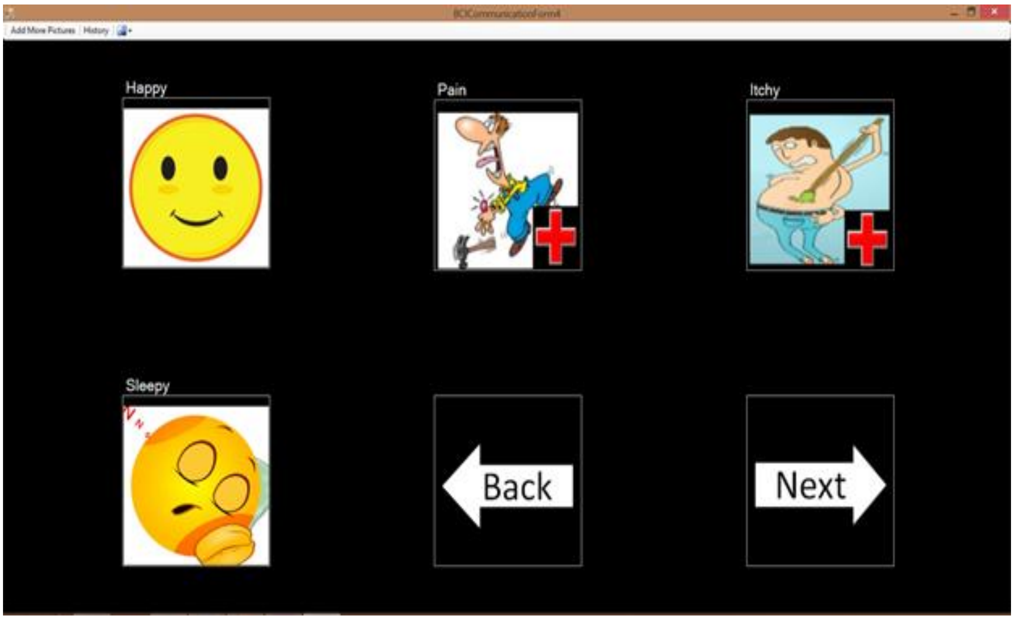


Figure 7: The screenshot showed the options for group heading of "Feelings" (layout 1).

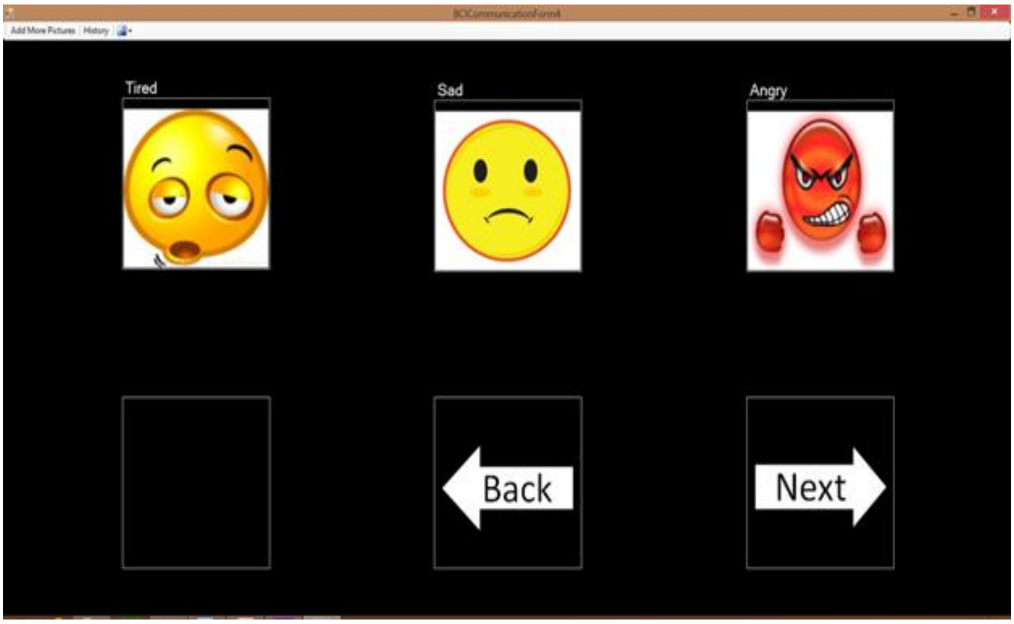


Figure 8: The screenshot showed the options for group heading of "Feelings" (layout 2).

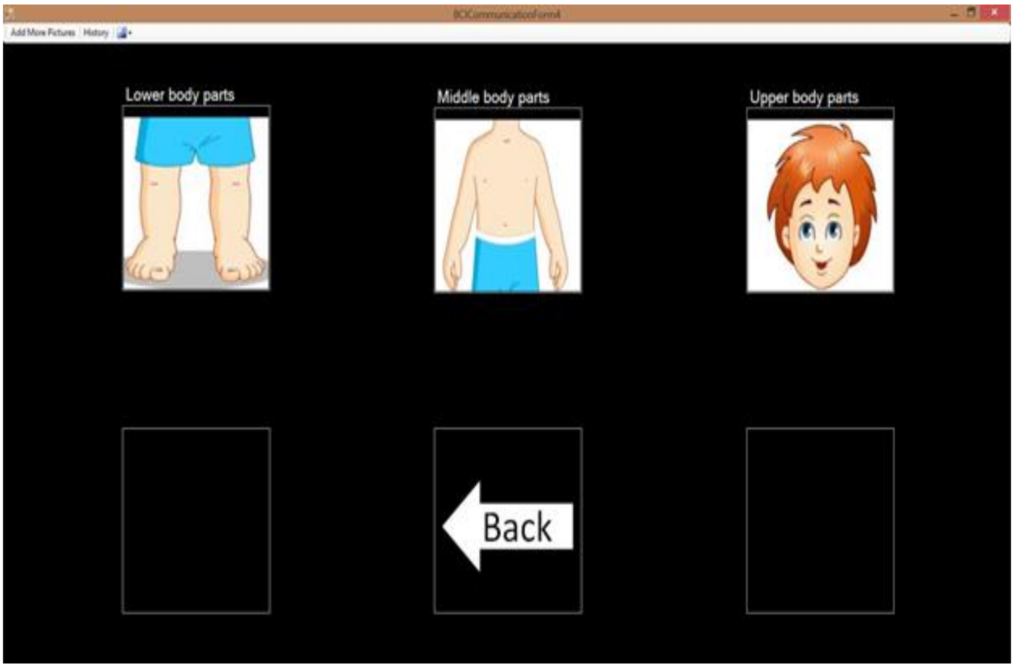


Figure 9: The screenshot showed the three groups of body parts options after picture of “Pain” or “Itchy” (in Figure 7) is selected.

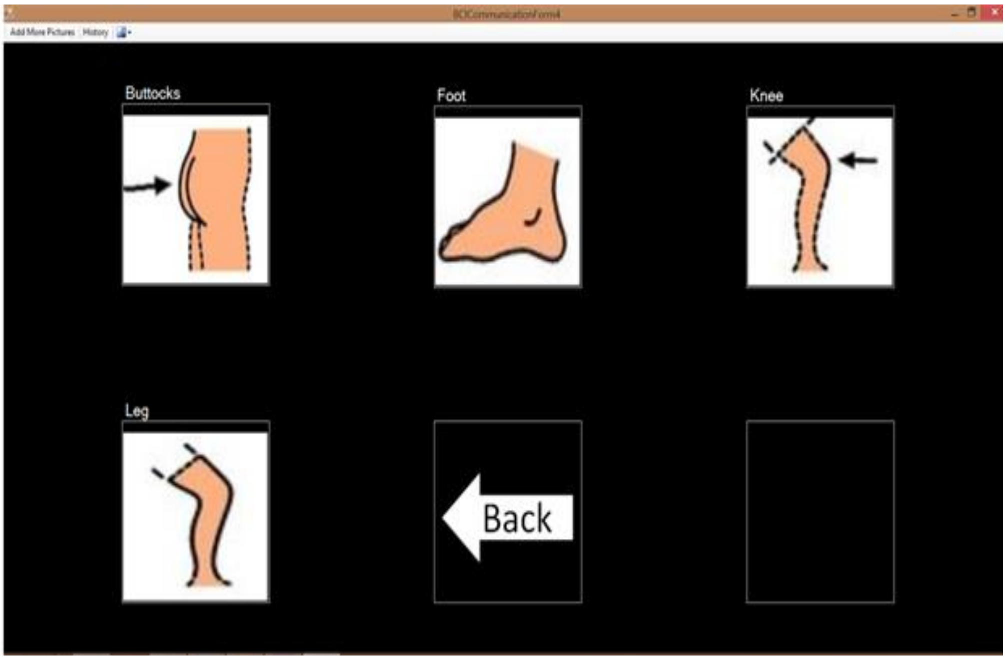


Figure 10: The screenshot showed the options for after picture of “lower body parts” (in Figure 9) is selected.

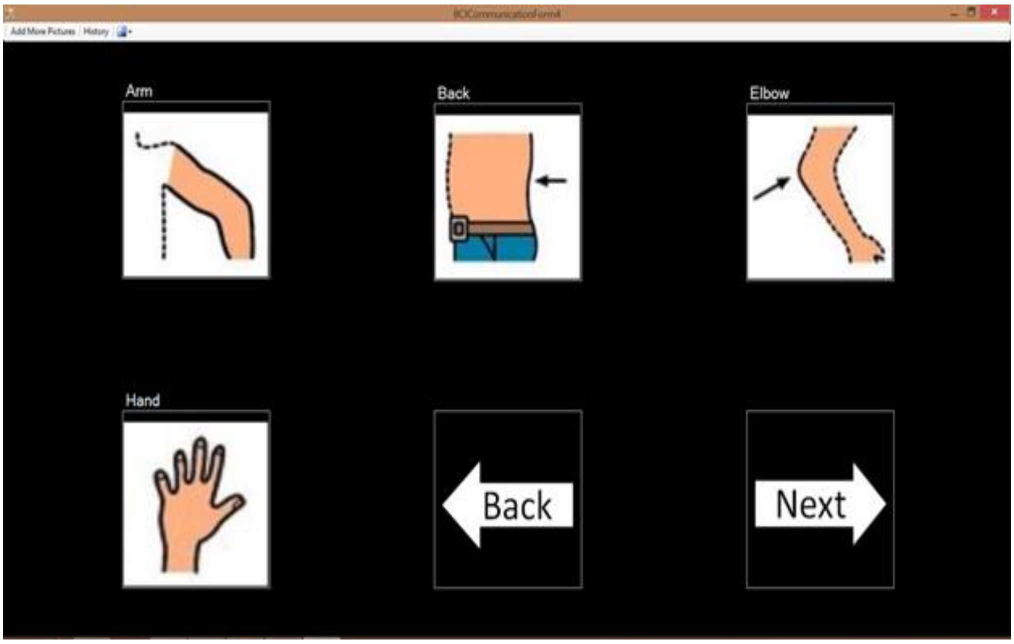


Figure 11: The screenshot showed the options for after picture of "middle body parts" (in Figure 9) is selected.

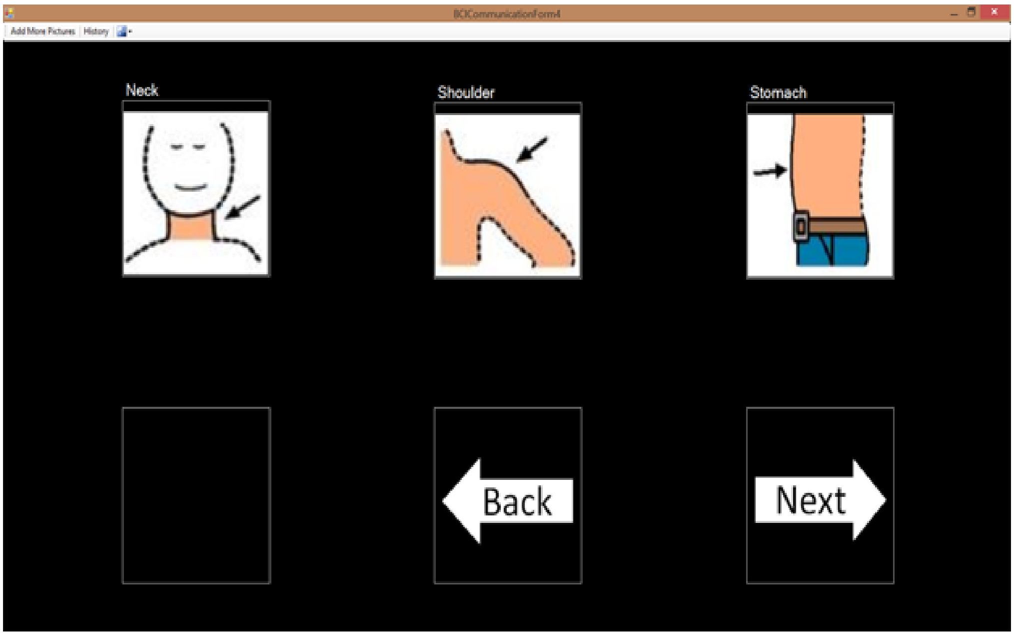


Figure 12: The screenshot showed the options for after picture of "upper body parts" (in Figure 9) is selected (layout 1).

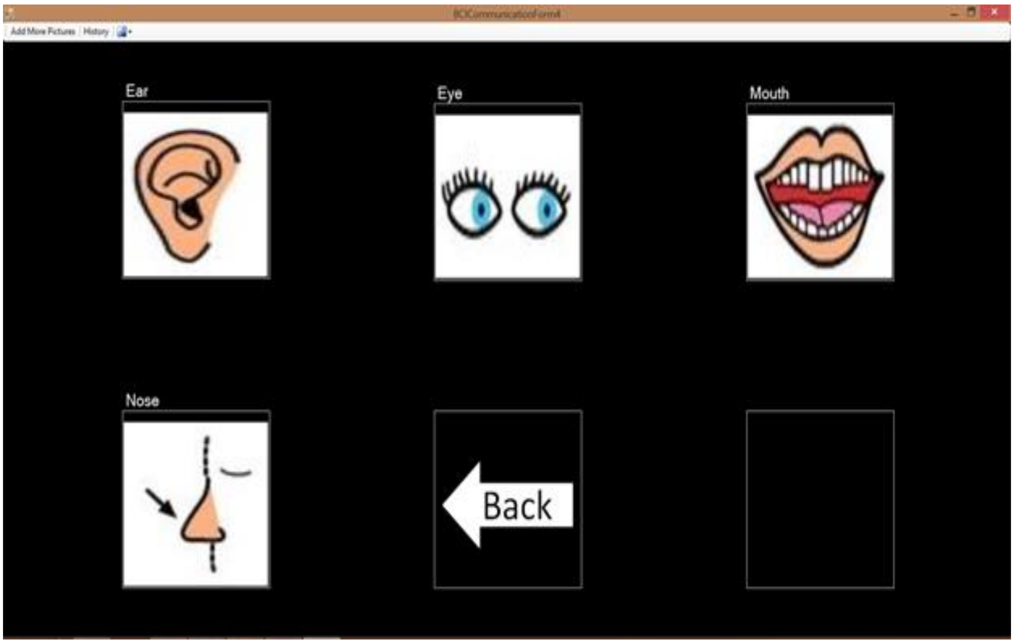


Figure 13: The screenshot showed the options for after picture of "upper body parts" (in Figure 9) is selected (layout 2).

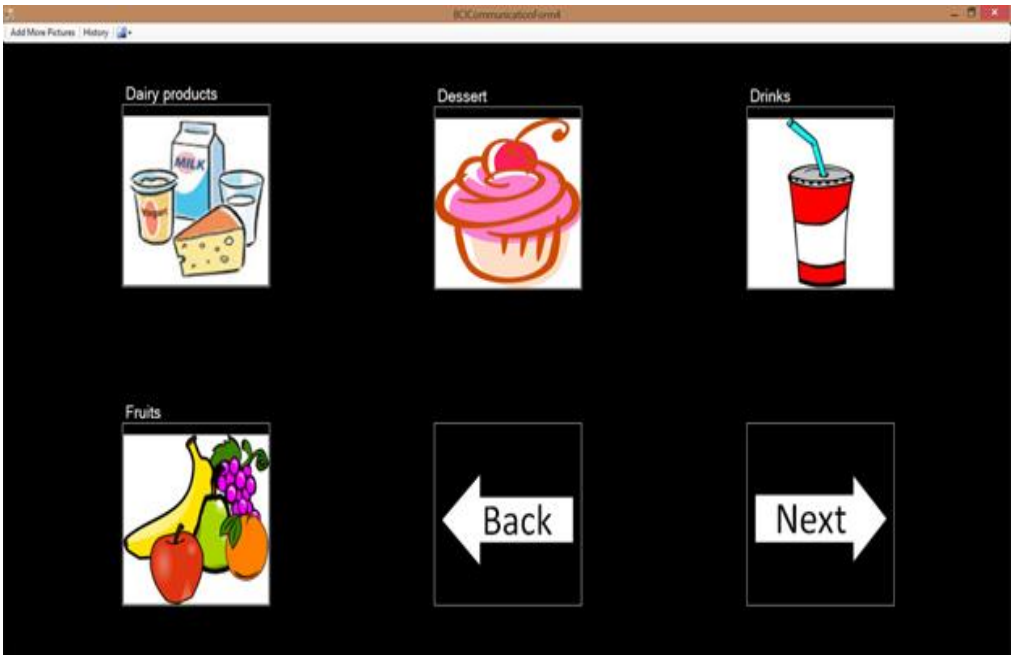


Figure 14: The screenshot showed the options for group heading of "Foods and Drinks" (layout 1).

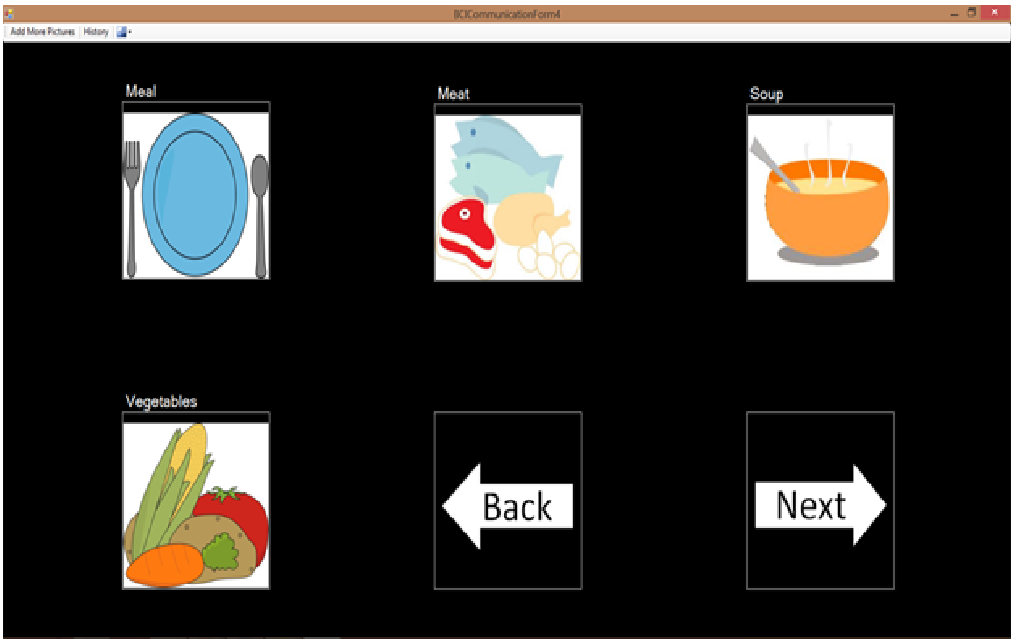


Figure 15: The screenshot showed the options for group heading of "Foods and Drinks" (layout 2).

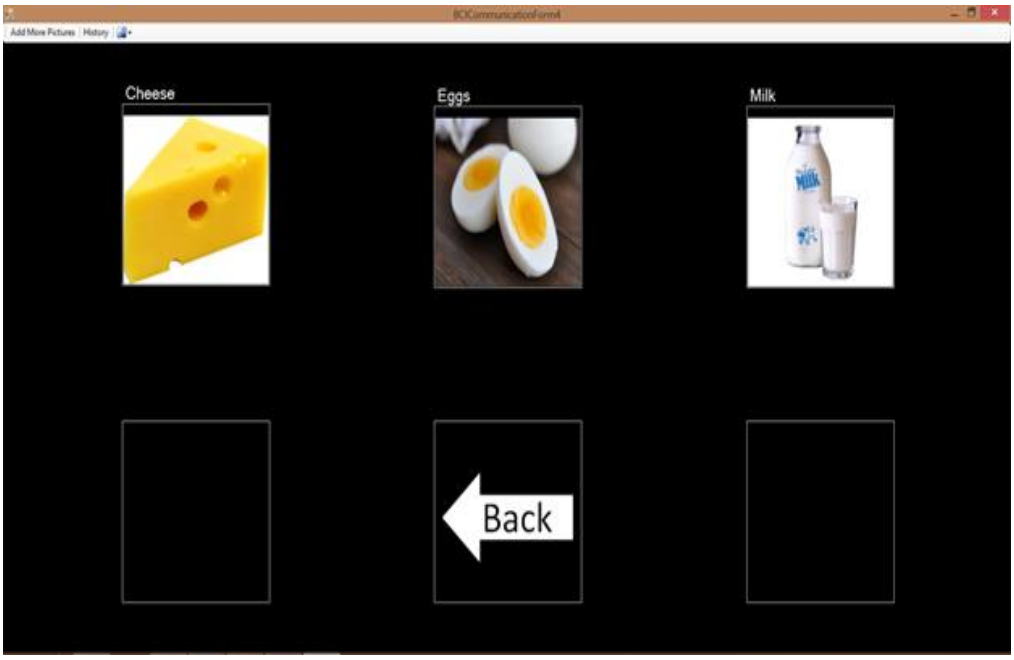


Figure 16: The screenshot showed the options after picture of "Dairy products" (in Figure 14) is selected.

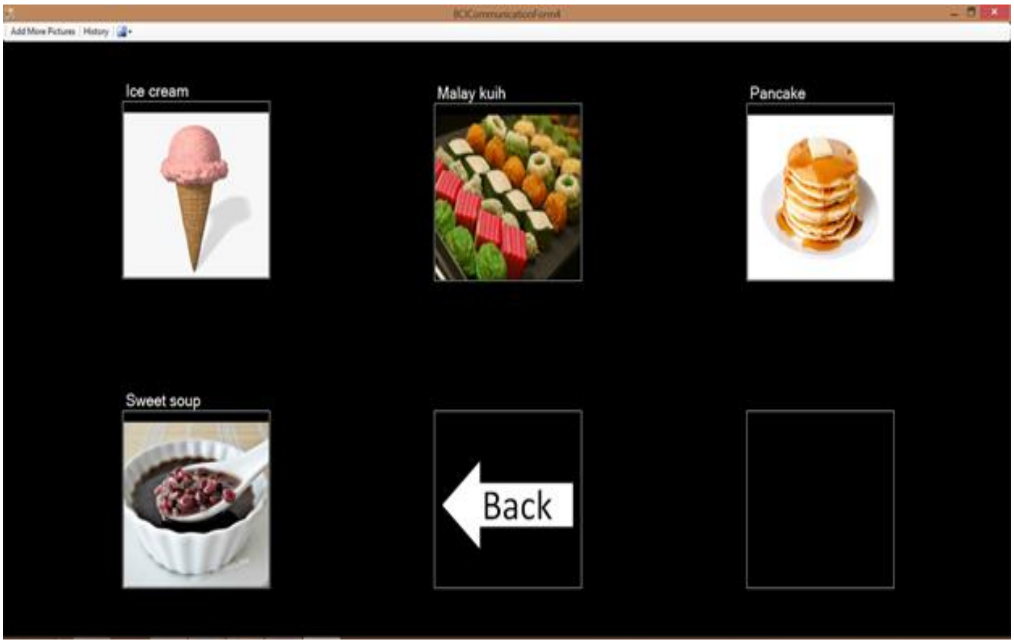


Figure 17: The screenshot showed the options after picture of “Dessert” (in Figure 14) is selected.

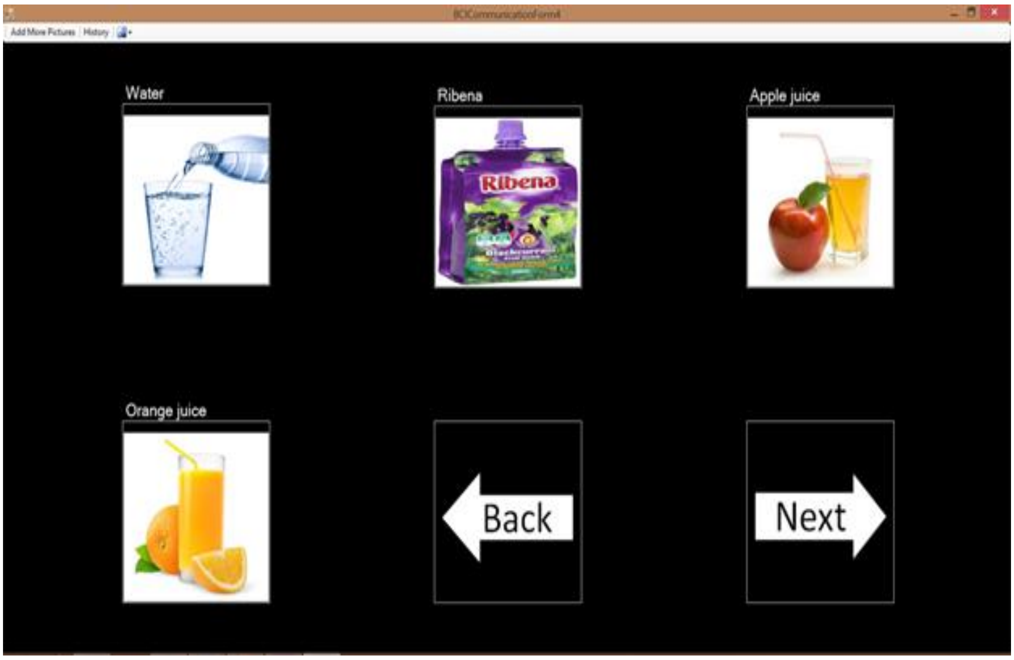


Figure 17: The screenshot showed the options after picture of “Drinks” (in Figure 14) is selected (layout 1).

Figure 18: The screenshot showed the options after picture of “Drinks” (in Figure 14) is selected (layout 2).

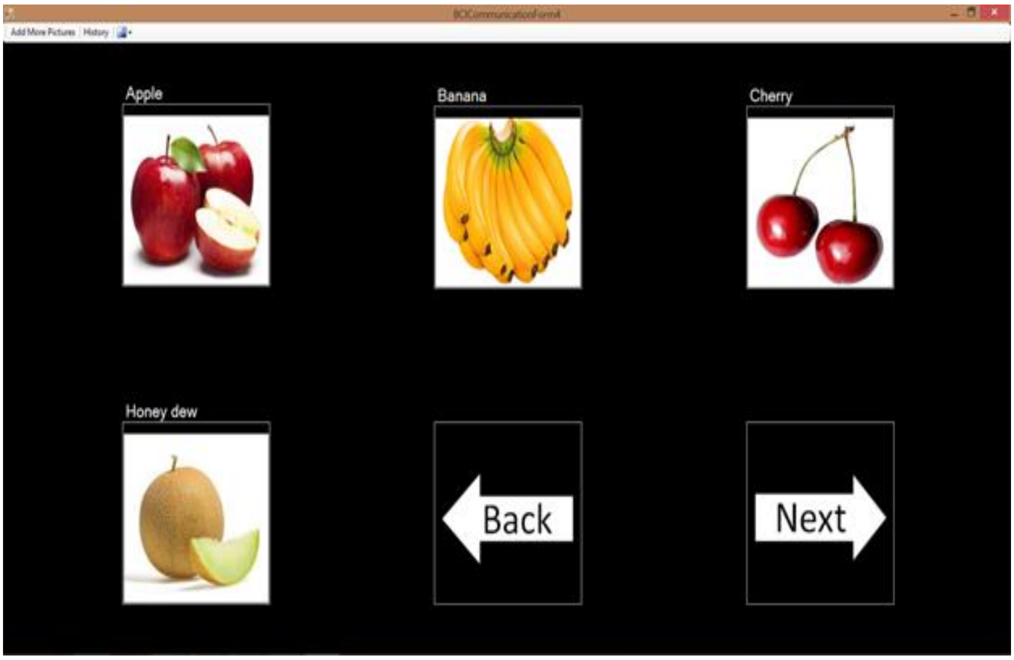


Figure 19: The screenshot showed the options after picture of “Fruits” (in Figure 14) is selected (layout 1).

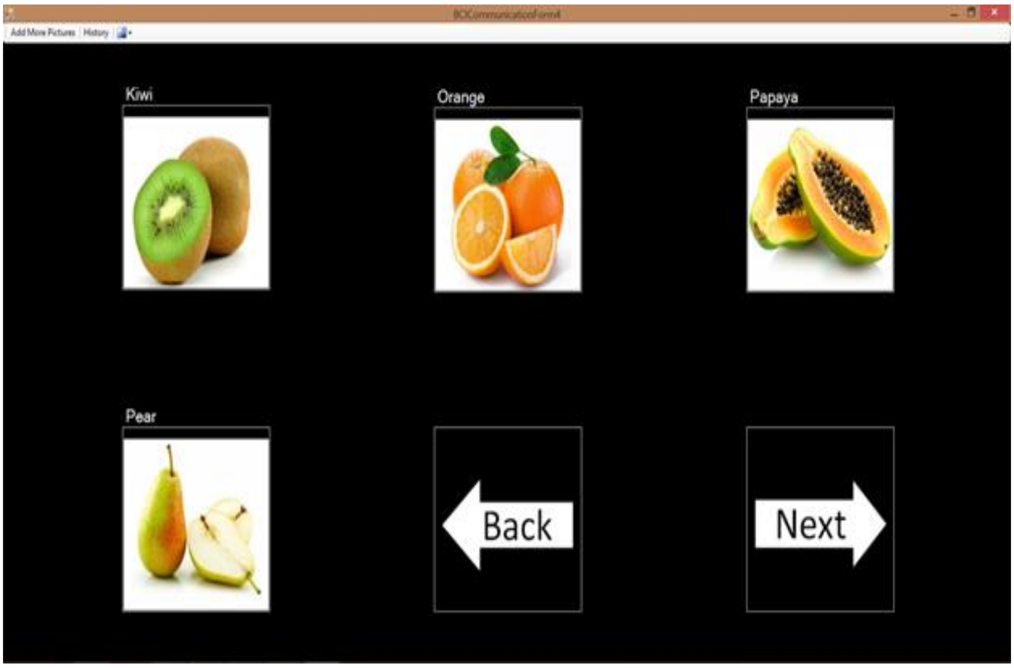


Figure 20: The screenshot showed the options after picture of “Fruits” (in Figure 14) is selected (layout 2).

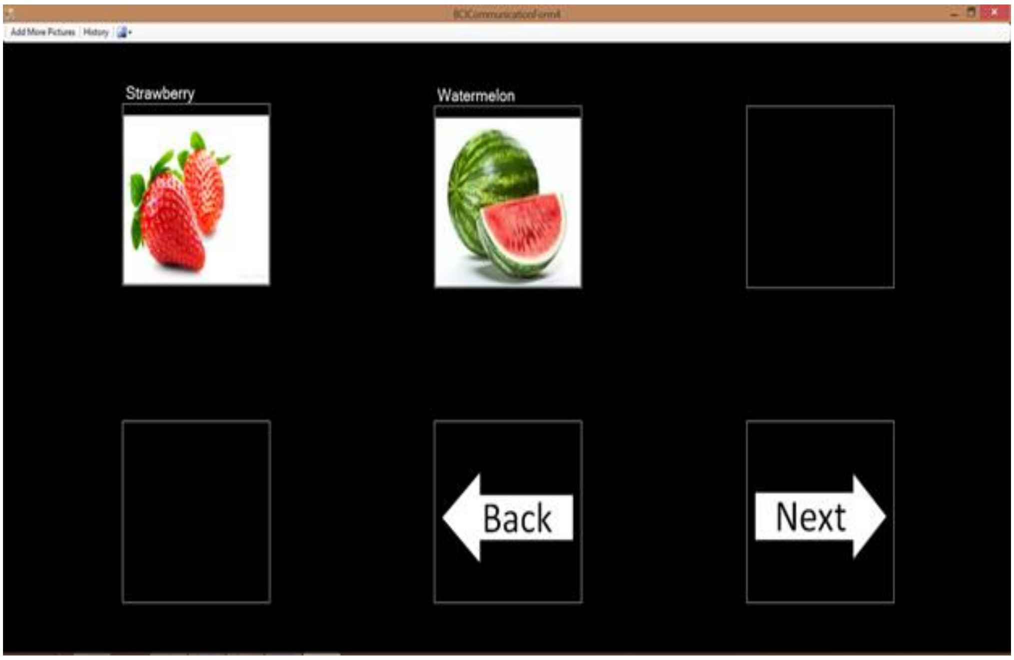


Figure 21: The screenshot showed the options after picture of “Fruits” (in Figure 14) is selected (layout 3).

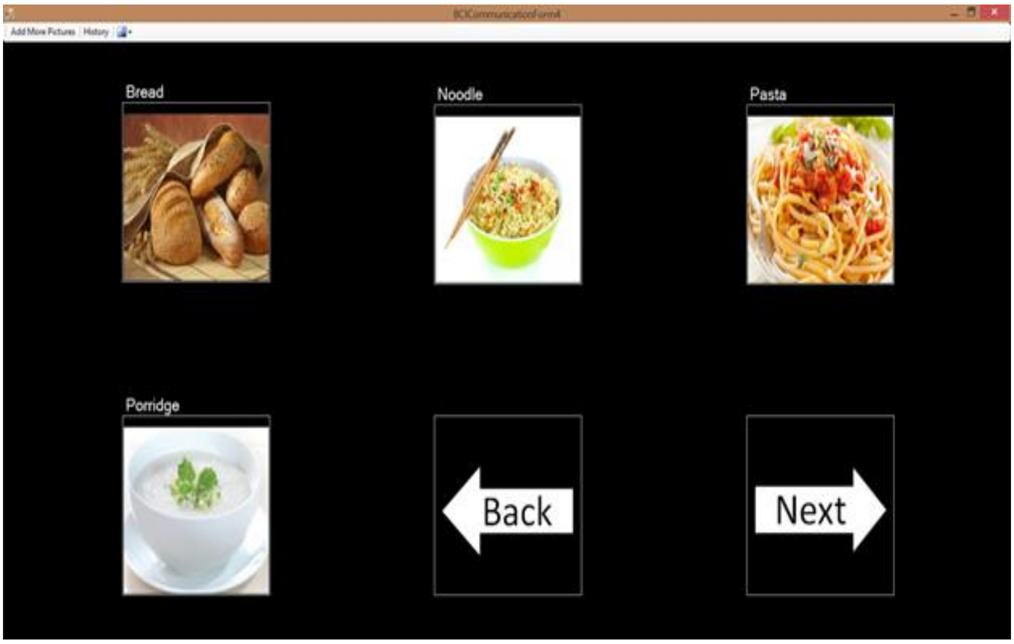


Figure 22: The screenshot showed the options after picture of "Meal" (in Figure 15) is selected (layout 1).

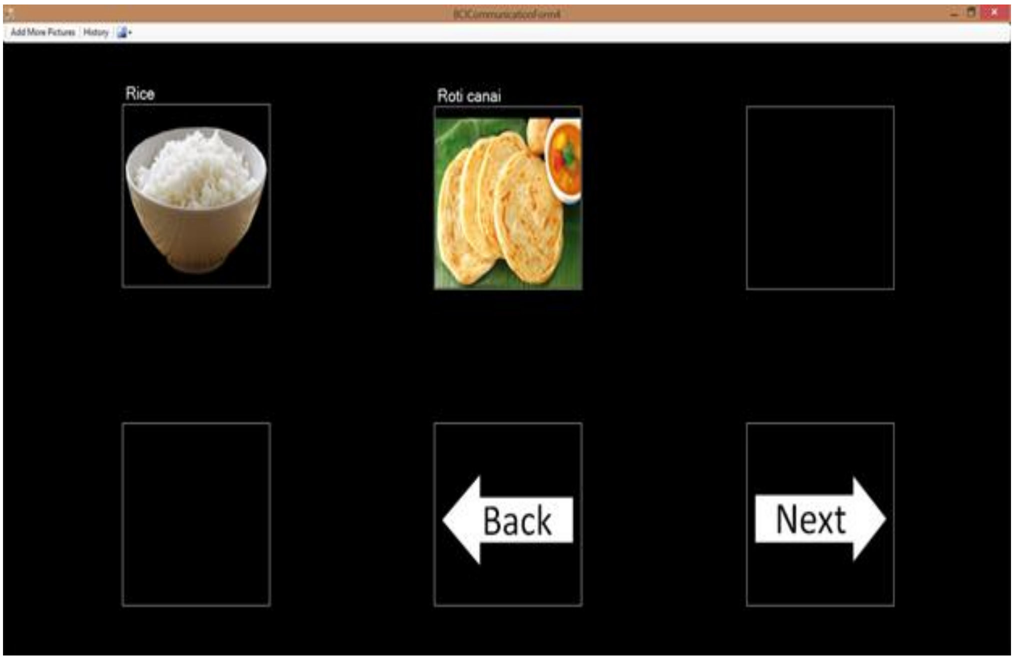


Figure 23: The screenshot showed the options after picture of "Meal" (in Figure 15) is selected (layout 2).

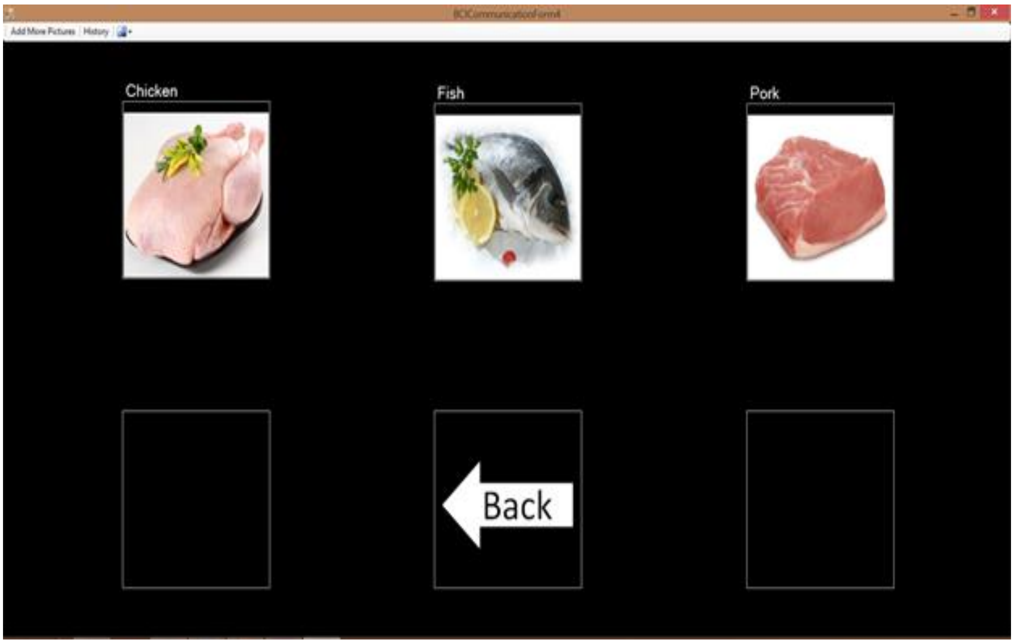


Figure 24: The screenshot showed the options after picture of “Meat” (in Figure 15) is selected.

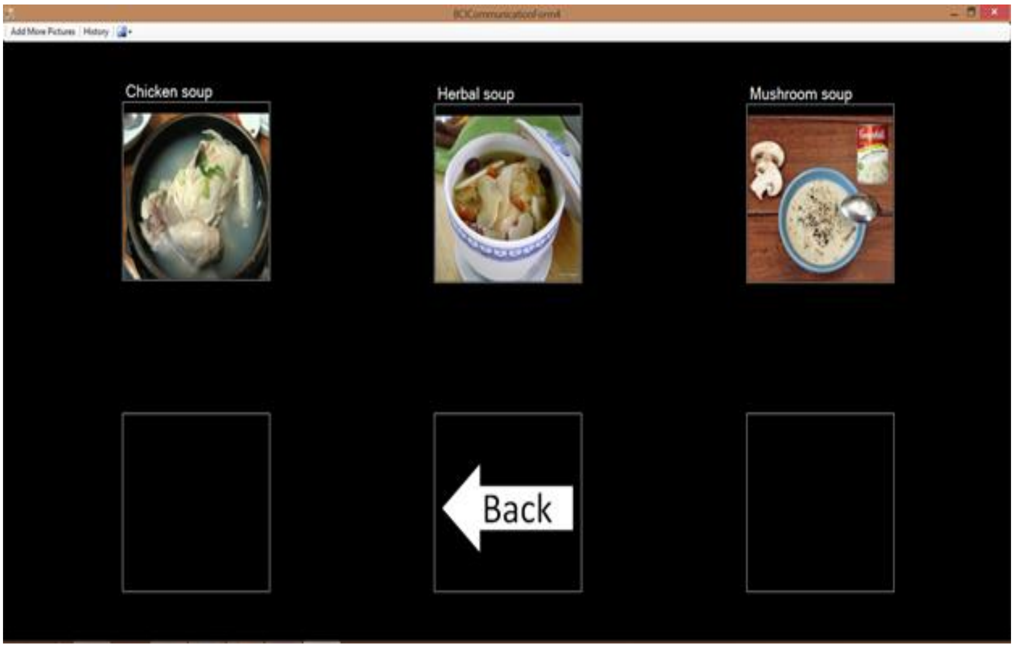


Figure 24: The screenshot showed the options after picture of “Soup” (in Figure 15) is selected.

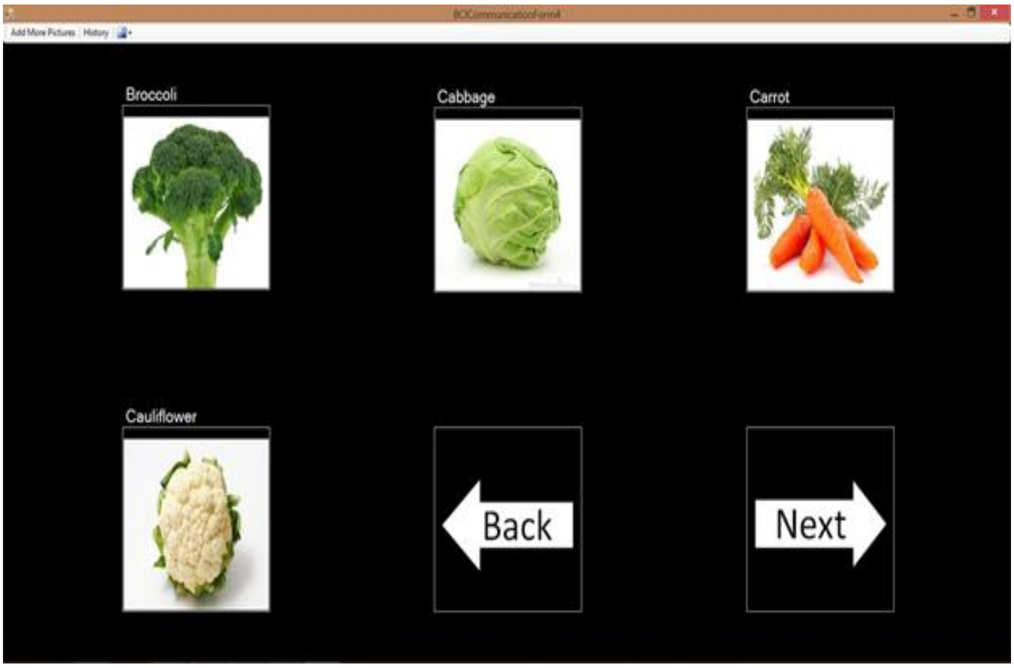


Figure 25: The screenshot showed the options after picture of “Vegetables” (in Figure 15) is selected (layout 1).

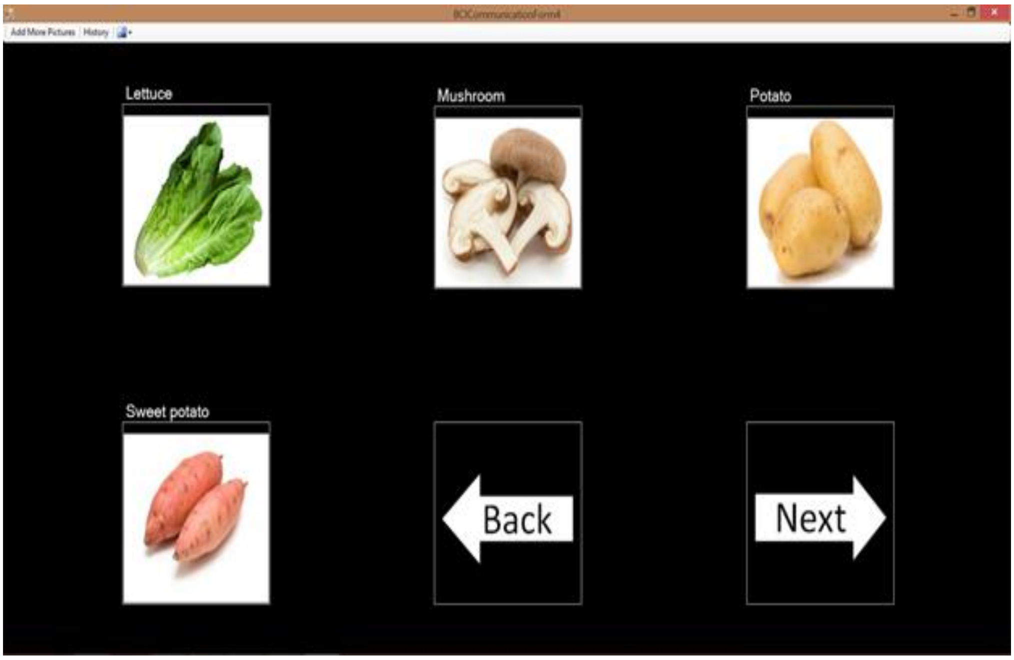


Figure 26: The screenshot showed the options after picture of “Vegetables” (in Figure 15) is selected (layout 2).

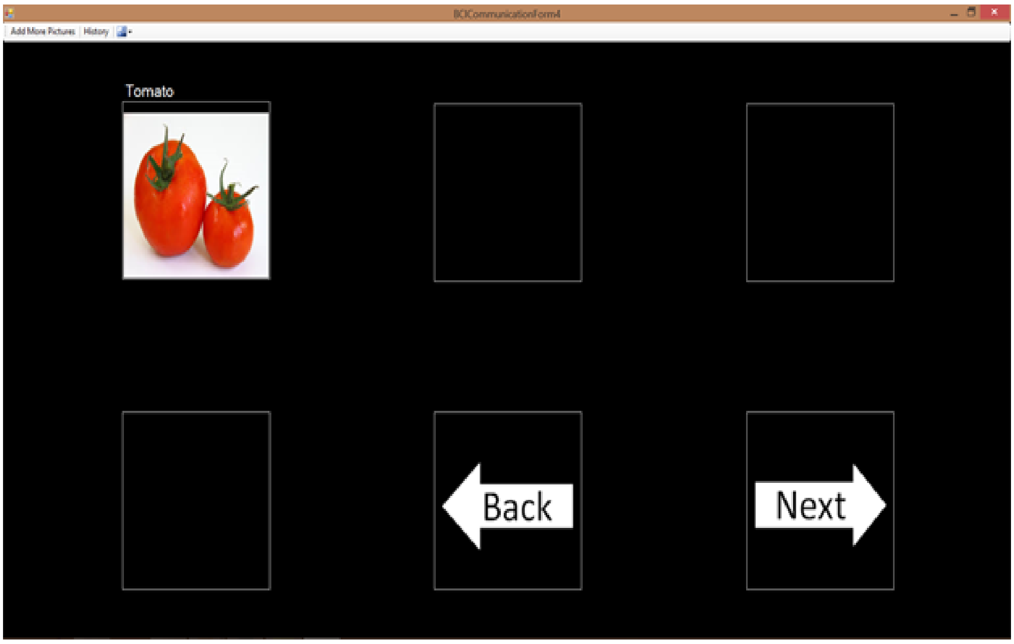


Figure 27: The screenshot showed the options after picture of “Vegetables” (in Figure 15) is selected (layout 3).

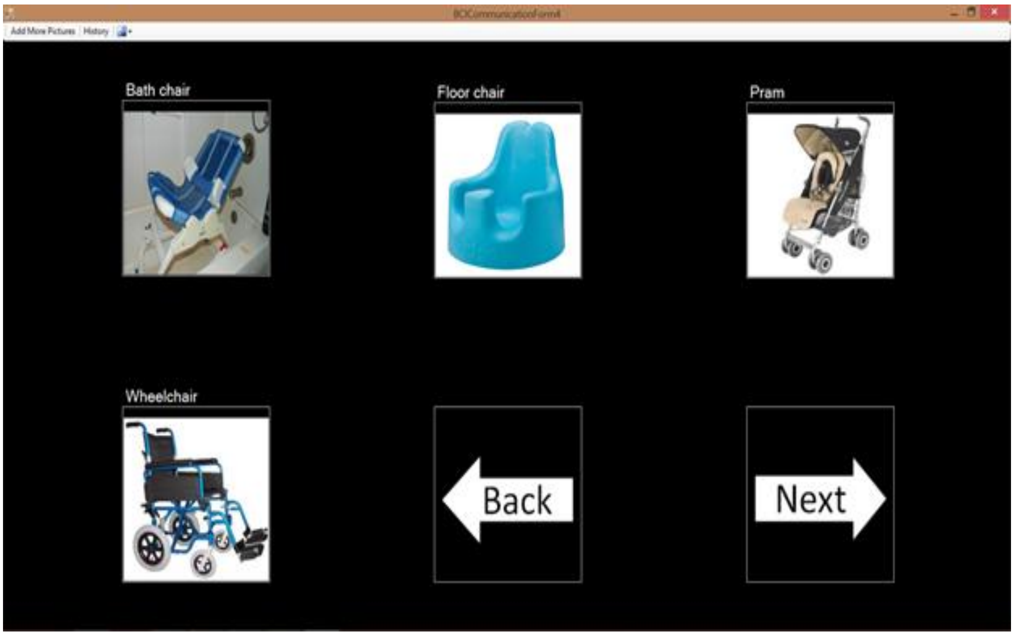


Figure 28: The screenshot showed the options after picture of “Mobility” is selected (layout 1).

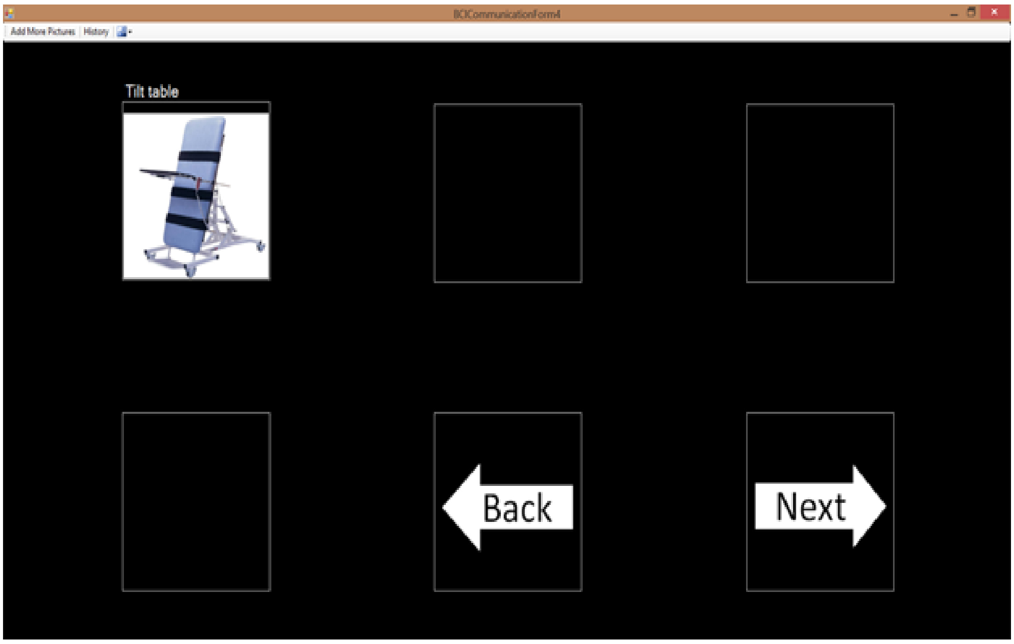


Figure 29: The screenshot showed the options after picture of “Mobility” is selected (layout 2).

APPENDIX D

PATIENT'S INTERVIEW FORM

Survey Form

Name: ________________________

Age: __________________________

Previous occupation: ________________

Date/ Month/ Year diagnosed with MND: ___________________________

1. Do you prefer a word-based or pictorial-based computer interface?

   ☐ Word-based

   ☐ Pictorial-based

2. What is your preferred language?

   ☐ English

   ☐ Malay

   ☐ Chinese

   ☐ Others (specify) ____

3. What are the physical symptoms that you are experiencing?

   ☐ Dry mouth

   ☐ Excessive salivation

   ☐ Tired

   ☐ Difficulties speaking

   ☐ Difficulties in swallowing

   ☐ Difficulties in chewing

   ☐ Breathing difficulties

   ☐ Shortness in breath

   ☐ Coughing

   ☐ Choking

1

☐ Difficulty using hand for daily activities. If use, specify what activities:

____

____

____

☐ Difficulties walking

☐ Inability to control emotions

☐ Difficulties with concentration

☐ Difficulties getting into sleep

☐ Difficulty turning in bed

☐ Pain (specify which parts of the body) ______________________

____

____

☐ Muscle weakness (specify which parts of the body) ______________

____

____

☐ Muscle stiffness (specify which parts of the body) ______________

____

____

☐ Muscle twitching (specify which parts of the body) ______________

____

____

☐ Others (specify) ___________________________________

____

____

4. Are you still able to talk clearly?

☐ Yes ☐ No ☐ Sometimes

5. Are you still able to walk?

☐ Yes ☐ No ☐ Sometimes

2

6. Are you still able to move your fingers?

☐ Yes ☐ No ☐ Sometimes

7. How do you currently express your needs/ feelings?

☐ Verbal communication
☐ Vocalizing
☐ Writing
☐ Facial expressions
☐ Eye movements/ eye blinks
☐ Others (specify) ____

____

____

8. What do you want for the following categories?

Personal care (E.g. extra length nail clippers, dressing aids, electric razor)

____

____

____

____

Personal mobility and movements (E.g. grab rails, walking aids, wheelchair)

____

____

____

____

Food and Drinks (E.g. eating rice, drinking, porridge)

____

____

3

9. Who are the people that you would like to meet up with?

____

10. What are the places that you wish to go (if possible)?

11. What are the entertainments you wish to have, radio, TV etc.?

12. What are the feelings that you wish to express?

- [ ] Hot
- [ ] Cold
- [ ] Bright
- [ ] Dark
- [ ] Itchy
- [ ] Pain
- [ ] Hungry
- [ ] Thirsty
- [ ] Better
- [ ] Blessed
- [ ] Calm
- [ ] Comfortable
- [ ] Relieved
- [ ] Secure
- [ ] Satisfied
- [ ] Thankful
- [ ] Touched
- [ ] Angry
- [ ] Bored
- [ ] Depressed
- [ ] Disappointed
- [ ] Fearful
- [ ] Frustrated
- [ ] Hopeless
- [ ] Ignorant
- [ ] Nervous
- [ ] Sad
- [ ] Uneasy
- [ ] Worse
- [ ] Worry
- [ ] Others (specify) ____________________

4

13. What are the activities that you think may help to calm you down when you are sad / depressed?

☐ Surfing photos
☐ Reading articles
☐ Listening to music
☐ Listening to prayers
☐ Others (specify) ______________________________

____

____

14. Other short-term/ long-term needs?

____

____

APPENDIX E

INFORMED CONSENT FORM

Participant Name: __________________ **I/C No**.: __________________

Contact No.: _________________ **Researcher Name**: _______________

You are invited to participate in the following study. Your participation into this study is entirely voluntary. Your participation may not benefit you directly but it will help us in improving the designs and operations of SSVEP-BCI system.

Title of Study: Performance of Brain-Computer Interface (BCI) communication system using steady-state visual evoked potential (SSVEP)

Purpose of Study: To investigate the effectiveness of the SSVEP-BCI communication system as a speller as well as for selecting words and phrases.

Procedures:

First, the researchers will place some EEG electrodes at certain locations on the participant's scalp based on the International 10-10 system of EEG sensor placement. The researcher will check the SSVEP of participant when looking at a flickering patch or patches on a computer screen. After that, the researcher will guide the participant to use the word/phrase selection and speller programs of the SSVEP-BCI communication system. The estimated duration for the experiment is about 1.5 hours including 30 minutes for setting up the EEG electrodes.

Potential Risks:

There may be some discomfort experienced by attaching the electrodes on the scalp or skin with electro-gel and secured with stickers. Under rare circumstances, people with very sensitive skin may have some minor irritation or redness on the skin in reaction to the application of electro-gel.

The participant may find the experiment to be uncomfortable and unpleasant because of the duration of the experiment and the nature of the experiment that requires the participant has to look at the flickering patches on the computer screen.

The participant may also have eye fatigue after continually looking at the flickering stimuli over a period of time.

Additionally, there is also a potential risk to induce cognitive side-effects including photo epileptic seizures by repetitive flickering stimuli modulated at certain frequencies.

The investigator will always check with the participant to determine if the participant is having any negative sensations during the experiment.

Confidentiality:

Information gathered from the study may be published or presented in public forums. However your name and other identifying information will not be used or revealed.

Researcher's Signature: ________________ Date: _________________

I have been fully informed and understood the above information. I have had the opportunity to discuss with the researcher and I have had my questions answered by him/her in a language that I understand. In signing this consent form, I agree to follow the procedures of the study, and I understand that my participation is voluntary, and I am free to withdraw my consent and discontinue my participation in this study at any time without any penalty.

I agree to take part in this study.

Participant's Signature: ______________________ Date: ________________

Relationship to Participant: ____________________
(If other than participant giving consent)

Witness Name: _________________ Witness Signature: _______________