

# Fuzzy-set Theory to Support the Design of an Augmentative and Alternative Communication Systems for Aphasia Individuals

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**Abstract**—This paper presents a new design of an Augmentative and Alternative Communication (AAC) systems for conveying delicate feelings or emotions of aphasia individuals, which is based on Fuzzy-set theory. Fuzzy-set theory is crucial in addressing the ambiguity of linguistic terms used and judgments made by aphasia individuals. Due to the communication difficulties of aphasia individuals, their insights were assigned in triangular fuzzy membership functions during the design process of AAC systems. In the proposed design of AAC systems, the delicate feelings or emotions were expressed as a scale, and candidate(s) of delicate feelings or emotions were shown based on their specified position. If the candidate(s) cannot properly convey the desired delicate feelings or emotions, then the corresponding fuzzy membership function can be realized by controlling its position. The proposed method has the advantage of being able to be conveyed the exact want and needs of delicate feelings or emotions during communication. Experimental result shows that conveying delicate feelings or emotions of the aphasia individual could be improved by 50 percent using the proposed design of AAC systems.

**Keywords**—Aphasia; augmentative and alternative communication; human factors; fuzzy-set theory

## I. INTRODUCTION

Aphasia is a speech and language impairment, caused by acquired brain damage [1]. A stroke is the most common cause of aphasia. It also caused by other types of acquired brain injuries include traumatic brain injuries, brain tumors, and anoxia. The incidence of aphasia after stroke is about 20% to 38% in the acute phase [2][3]. Moreover, brain damage often causes hemiparesis, which is a weakness or inability to move on one side of the body. Basically, right-sided hemiparesis involves injury to the left side of the brain, which controls language and speaking. People with this type of hemiparesis may have trouble speaking and/or understanding what people are saying.

Depending on the specific locations of brain damage, the severity and pattern of aphasic symptoms vary from person to person. Broca's type aphasia is called non-fluent aphasia. They have difficulty in speaking. Wernicke's type aphasia is called fluent aphasia. They have difficulty in understanding. However, speech-language therapist (SLT) supports aphasia individuals to perform their daily activities.

Aphasia affects individuals' ability to speak, to understand speech, to read and to write. These language difficulties seriously hamper their daily communications [4]. It is noted that other disabilities caused by brain damage such as motor speech disorder (e.g., dysarthria, dysphonia or apraxia of speech) affect intellectual capabilities. People with these disabilities have no difficulties in finding the words they wish to say, and they report no difficulties with reading, writing, or auditory comprehension. On the other hand, aphasia individuals cannot communicate properly by their own words because their brain areas are restricted to process primarily speech and language, but their intelligence is intact. Thus, communication barriers often stigmatized disabled people and can further exacerbate the difficulties in quality of life (QOL) [1]. Consequently, aphasia individuals live at home with their families after they leave the hospital. During this time, a speech-language therapist (SLT) supports the aphasia individuals to improve their communication. SLT supports aphasia individuals based on the diverse symptoms such as non-fluent, fluent, mild, moderate, severe, unable to read, unable to write or unable to understand. SLT supports them in various ways of alternative communication such as memo writing, using picture boards, picture cards or gestures, which are examples of AAC systems. Although these types of support of SLT through rehabilitation improve the communication skills of aphasia individuals, they still cannot convey their delicate feelings or emotions to others by the current AAC systems.

Basically, AAC systems include pictures and symbols, which use electronic devices to adapt voice output communication aids, methods, and techniques [4]. In this regard, several computer applications and many portable devices are available for such communication support. As a result, AAC system is now widely used on available mobile devices, tablets, and PCs. [5]. For example, Proloquo2Go is a common AAC system based on a folder structure, each displaying a box with images and symbols, or providing a text typing input box [6]. A selected symbol can be spoken with natural sounds or via a machine voice. The main problem of the existing AAC systems is the difficulty expressing the exact wants or needs by the aphasia individuals with their delicate feelings or emotions. The reason is that the design process of popular design approaches cannot include the insights of aphasia individuals in the AAC systems because of their

communication difficulties. To solve this problem, Fuzzy-set theory can support the design of the AAC systems to include the insights of aphasia individuals to convey their delicate feelings or emotions.

The popular design approaches to design AAC systems for disabled people are Barrier-free Design, Universal Design, Design for All or Inclusive Design. Barrier-free Design is specially introduced to remove architectural obstacles for disabled people [7][8]. On the other hand, Universal Design and Design for All look for a design solution that can support everyone including people with disabilities [9][10]. However, Universal Design is insufficient to cover everyone's needs. First, designers acquire needs of product or environment from different user groups including those with disabilities. Then designers identify common needs that can support all user groups. Designers think that design solutions are enough to fulfill these common needs. Finally, designers complete a design with these common needs. As a result, disabled users' needs are partially included in the common needs of Universal Design solutions. Nevertheless, these common needs are not sufficient to fulfill disabled users' needs. Thus, disabled users cannot use the design solutions. It is noted that these disabled users are extreme users because they represent the extreme end of the usability spectrum and are most affected by poor design solutions as shown in Fig. 1. Extreme users may have exaggerated needs, thought or behavior compared to the typical users. In addition, extreme users can offer unique insights about the products and inspire a different way of thinking about current and future users. For this reason, Universal Design seems impractical and ineffective for extreme users with common views of the design [11].

On the other hand, Inclusive Design is an approach of designing with extreme users to find different ways for the access of products or environments. In Inclusive Design, insights of extreme users' need to be included in the products or environments. Therefore, this study used inclusive design to include the insights of aphasia individuals in the AAC systems. However, the insights of an aphasia individuals are not included properly in the AAC systems at the design process of Inclusive Design. Here, insights of aphasia individuals are delicate feelings or emotions. Although an aphasia individual can identify wants and needs from their experiences, they cannot express them to the designer. As a result, their exact wants and needs are not met by existing design. Only the aphasia individual can give insights into different ways of participation to access the AAC systems but other people like designer, SLT or proxies cannot include an aphasia individual's insights. Consequently, design cannot cover the expectation of aphasia individuals to access the AAC systems in different ways. Therefore, design process of AAC systems needs support to improve communication skills of aphasia individuals. To address the above-mentioned issues, this study used Fuzzy-set theory to support the design process of AAC systems for aphasia individuals regardless of their communication difficulties. In other words, Fuzzy-set theory includes the delicate feelings or emotions of aphasia individuals to support the design of AAC systems.

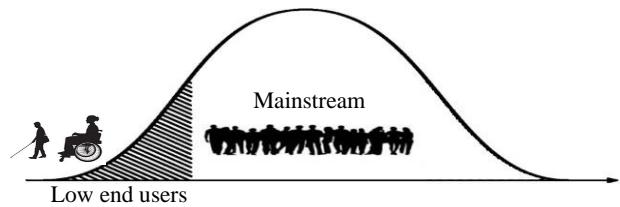


Fig. 1. Usability Spectrum of Product or Environments.

## II. RELATED WORK

The majority of previous studies used User-centered Design (UCD) or Participatory Design (PD) approaches to design an AAC systems [12][13][14]. Most UCD and PD methods make fundamental assumptions about the communication skills of those who will participate. They are founded on the premise that participants will have the requisite skills, for example, to communicate orally, to understand and produce written text, to comply with instructions. Those who do not have these skills cannot readily participate. Therefore, these AAC systems cannot fulfill the needs of aphasia individuals.

Several AAC systems have been developed using HCD or PD to assist people with aphasia, but a small number of AAC systems have been designed to assist communication for people with aphasia. Mahmud et al. implemented an email tool for language impairments using UCD approach [15]. Their tool was developed for sending email where other tasks cannot be performed. Thus, this tool is insufficient to assist other task for daily activities of diverse disabled users. Those that have used a PD approach to design have mostly used proxies. In other words, either SLT played the roles of the aphasic participant or the caregivers of aphasic participants provided feedback. For example, SLT played as proxies for aphasia users in the development of PhotoTalk [16], an application that allows people with aphasia to capture and manage digital photographs to support face-to-face communication. Thus, designers were able to specify only few real user requirements for diverse aphasia individuals. Koppenol et al. similarly designed an application that uses photographs to support communication and used SLT as proxies [17]. Kane et al. design a context-aware communication tool for improving interpersonal communication for people with aphasia [18]. They used PD at the design process, but they considered only two context such as current location and conversation partner. Hossain et al. also designed a context-aware communication tool to assist people with aphasia for improving their communication skills [19]. They used context history to get suggestion during communication. In the above-mentioned AAC systems, either the SLT played the roles of aphasic participants or the caregivers of them provided feedback to the designers. As a result, the design of AAC systems can partially fulfill the needs of aphasia individuals because they are implemented based on the common needs. Thus, many aphasia individuals still cannot convey their exact needs and wants with their delicate feelings or emotions using the existing AAC systems. The reason is that the insights of aphasia individuals did not consider at design process. In other words, aphasia individuals can only provide their insights in Fuzzy form which are not included by designers or SLT. For this reason, Fuzzy-set theory is crucial to

collect the insights of aphasia individuals from the real participants in the design of AAC systems. Therefore, the objective of this paper is to design an AAC system with the support of Fuzzy-set theory.

### III. METHODS

The overall design process of AAC systems is shown in Fig. 2. The process starts from the identification of interaction problems of old design. Then the design solution is implemented using the insights of aphasia individuals for conveying delicate feelings or emotions. Finally, the design solution is evaluated by aphasia individuals.

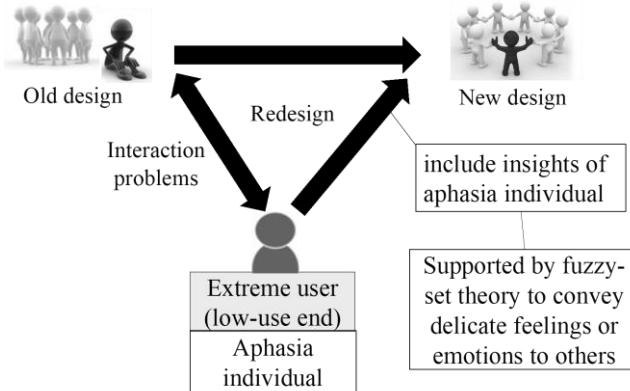


Fig. 2. The Design Process for AAC Systems for Aphasia Individuals.

#### A. Identification of Interaction Problems for Conveying Delicate Feelings or Emotions

The identification of interaction problems is completed by aphasia individuals as extreme users through a survey questionnaire. The survey questionnaire is offered to the aphasia individuals about delicate feelings or emotions. We would like to ask about 1) How much important is it to convey delicate feelings to others in order to actively participate in society? 2) How much can they convey their delicate feelings to others? and 3) How much can they understand the feelings of others? The interaction problems are identified based on the responses of each aphasia individual.

#### B. Redesign for Conveying Delicate Feelings or Emotions

The purpose of design is to include the insights of aphasia individuals for sufficient communication. In this study, the insights of aphasia individuals are delicate feelings or emotions. Aphasia individuals have difficulties to express their own thoughts verbally. Due to their difficulties, the delicate feelings or emotions are specified in fuzzy membership functions. Basically, they indicate delicate feelings or emotions on the scale of survey questionnaire during redesign. Their indicated positions for delicate feelings or emotions are not appropriate. Thus, a small amount of distance  $\Delta x$  needs to be managed so that fuzzy membership functions fit more based on their situations.

Aphasia individuals can convey their delicate feelings or emotions by pointing to a scale instead of their own voice. Basically, the scale represents the in-between situations (e.g. physical conditions, tiredness, etc.) of aphasia individuals. Thus, the delicate feelings or emotions were expressed after the

redesign as a scale, and candidate(s) of them were shown based on his/her specified position as shown in Fig. 3. If the candidate(s) cannot properly convey their delicate feelings or emotions, then the corresponding function can be realized by controlling its position from  $x$  to  $(x+\Delta x)$  or  $(x-\Delta x)$  to adjust his/her delicate feelings or emotions.

$$\mu_{\tilde{M}}(x) = \begin{cases} 0 & x < \alpha \\ \frac{x-\alpha}{\beta-\alpha} & \alpha \leq x \leq \beta \\ \frac{\gamma-x}{\gamma-\beta} & \beta \leq x \leq \gamma \\ 0 & x > \gamma \end{cases} \quad (1)$$

To allocate the fuzzy membership functions for corresponding delicate feelings or emotions, they provide their insights during design as shown in Fig. 3. The membership functions of these fuzzy sets are denoted by equation (1), where  $(\alpha, \beta, \gamma)$  denote the left-hand number, middle number, and right-hand number of each candidate of delicate feelings or emotions, respectively. For example, the triangular fuzzy number for ‘very bad’ can be represented by 0, 1, 1.5 as shown in Fig. 3. The triangular fuzzy membership numbers for delicate feelings or emotions are shown in Table I. The order of candidate(s) will be displayed according to the maximum possibility value of each candidate. The overall procedure for conveying delicate feelings or emotions based on the pointed location of aphasia individuals is represented in Fig. 4.

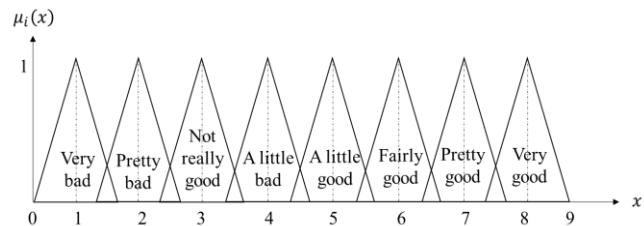


Fig. 3. Delicate Feelings or Emotions in Triangular Fuzzy Membership Function based on the Opinions of Aphasia Individuals.

TABLE I. TRIANGULAR FUZZY MEMBERSHIP NUMBERS FOR CONVEYING DELICATE FEELINGS OR EMOTIONS

Delicate feelings or emotions	Triangular fuzzy number
Very bad	(0, 1, 1.5)
Pretty bad	(1.25, 2, 2.5)
Not really good	(2.25, 3, 3.5)
A little bad	(3.25, 4, 4.5)
A little good	(4.25, 5, 5.5)
A fairly good	(5.25, 6, 6.5)
Pretty good	(6.25, 7, 7.5)
Very good	(7.25, 8, 9)

For example, an aphasia individual feels ‘Not really good’ and he wants to convey it to others. When aphasia individuals point an area between ‘very bad’ and ‘very good’ for physical condition, the possible candidates of delicate feeling are regarded as ‘Pretty bad’ and ‘Not really good’ based on the procedure as shown in Fig. 4. These candidates are displayed as shown in Fig. 5 from the Table II. Suppose the possibility

value for these two candidates ‘Pretty bad’ and ‘Not really good’ are 0.5 and 0.3, respectively. The candidate ‘Pretty bad’ holds the top position of the list. The aphasia individual realized that the candidate ‘Not really good’ is not on the top position. He/she moves the pointed location of fuzzy membership function from  $x$  to  $(x+\Delta x)$  or  $(x-\Delta x)$  to adjust his/her delicate feelings or emotions.

Step 1:	Identify $I$ and $\mu_i(x), \forall i \in I = \{1, 2, \dots, n\}$ . Here, $I$ is the index of delicate feelings or emotions $\mu_1(x), \mu_2(x), \mu_3(x), \dots, \mu_n(x)$ . $n$ is the no. of index.
Step 2:	Ask a question to the aphasia individual about his/her current conditions.
Step 3:	Ask him/her to answer the question with a pointed location $x$ .
Step 4:	For the pointed location $x$ , calculate $\mu_i(x), \forall i \in I$ . Identify the Set $I' = \{i \mid \mu_i(x) > 0\}$ .
Step 5:	Show him/her the list of delicate feelings or emotions corresponding to $i' \in I'$ .
Step 6:	If the aphasia individual selects his/her desired delicate feelings or emotions as $i''$ index from $I'$ . Then, go to Step 7. Otherwise, go to Step 8.
Step 7:	For all $x$ , set $\mu_{i''}(x) := \mu_{i''}(x + \Delta x)$ or $\mu_{i''}(x) := \mu_{i''}(x - \Delta x)$ . Go to Step 10.
Step 8:	For all $i \in I'$ , set $\mu_i(x) := \mu_i(x + \Delta x)$ or $\mu_i(x) := \mu_i(x - \Delta x)$ . Go to Step 9.
Step 9:	Repeat steps 3 to 6 for new candidate list of delicate feelings or emotions.
Step 10:	End procedure.

Fig. 4. Procedure for Conveying Delicate Feelings or Emotions by Fuzzy-Set Theory.

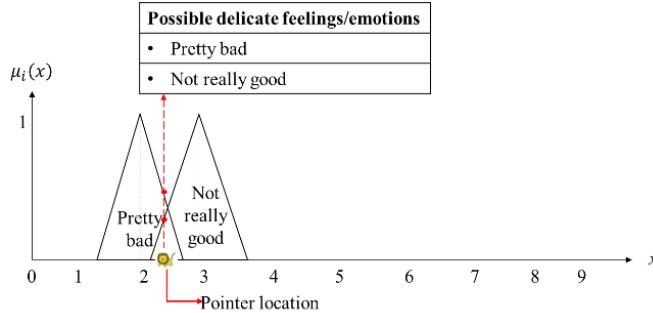


Fig. 5. Pointed Location and Corresponding Delicate Feelings or Emotions.

The possibility values of candidate are changed to 0.4 for ‘Not really good’ and 0.2 for ‘Pretty bad’ as shown in Fig. 6. Thus, the candidate ‘Not really good’ holds the top position of the candidate list.

### C. Case Study to Support the Design an AAC Systems by the Fuzzy-set Theory

A case study was conducted through survey questionnaires with the participation of two aphasia individuals for conveying delicate feelings or emotions. A prototype for conveying physical conditions and tiredness was also provided with the survey questionnaires. The purpose of the first survey questionnaire was to identify the interaction problems for conveying delicate feelings or emotions. The second survey questionnaire was used to allocate the fuzzy membership functions for the corresponding delicate feelings or emotions for sufficient communication. Finally, the prototype was

improved based on the interaction problems and the fuzzy membership functions through redesign.

TABLE II. DELICATE FEELINGS OR EMOTIONS TO CONVEY PHYSICAL CONDITIONS AND TIREDNESS

Feelings or emotions about	Delicate feelings	
	Worst to usual	Usual to best
Physical condition	Very bad	Very good
	Pretty bad	Pretty good
	Not really good	A fairly good
	A little bad	A little good
Tiredness	Quite tired	Not a little tired
	Very tired	Not tired at all
	Somewhat tired	Not so tired
	A little tired	Not too tired

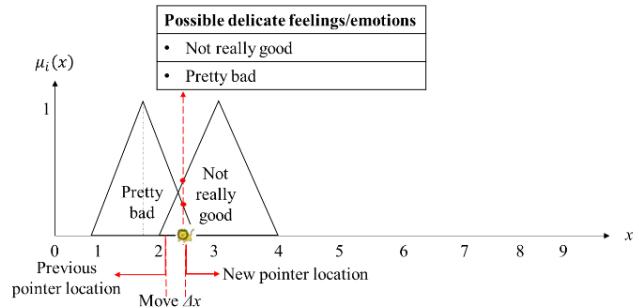


Fig. 6. After Moving the Pointer  $\Delta x$ , the New Pointed Location and Corresponding Delicate Feelings or Emotions.

TABLE III. RESPONSES OF SURVEY QUESTIONNAIRE FROM TWO APHASIA INDIVIDUALS

Questions	Responses	
	Aphasia individual 1	Aphasia individual 2
How much important is it to convey delicate feelings to others in order to actively participate in society?	Can do a little	Can do a little
How much can you convey the delicate feelings to others?	Can do a little	Can do a little
How much can you understand the delicate feelings of others?	Somewhat important	A little important
How much can you convey physical conditions to others?	Can do some extent	Can do some extent
How much can you understand physical conditions of others?	Cannot do	Cannot do
How much important to convey the physical conditions to actively participate in society?	Very important	A little important
How much can you convey tiredness to others?	Can do some extent	Cannot do
How much can you understand the tiredness of others?	Can do a little	Cannot do
How much important to convey the tiredness to actively participate in society?	Very important	Unimportant

#### D. Identification of Interaction Problems for Conveying Delicate Feelings or Emotions

To identify interaction problems, the responses of two aphasia individuals were collected as shown in Table III. From the two participants, the first aphasia individual is male, and he is 58 years old. He suffered from Broca's aphasia with the problem of memory impairment. He suffered from two strokes, one in March 2015 and another in November 2016. He can communicate with others, but his speech is non-fluent. He lives at home with his wife and children. The second aphasia individual is also male, he is 40 years old. He suffered from stroke at February 2018. He lives with his mother. He can communicate with others with a little fluent speech by rehabilitation. Thus, he returned his job. From the viewpoint of second aphasia individual, the provided prototype will be useful to more severe aphasia individuals than him.

The first aphasia individual responded that it was important in some extent for him to convey delicate feelings or emotions to others. He can communicate with others, but his speech is non-fluent. It was also very important for him to convey his physical conditions and tiredness to others in order to actively participate in society. He could convey his physical conditions and tiredness in 'some extent' to others. He could understand the tiredness 'a little', but he could not understand physical conditions of others. He also has memory impairment with Broca aphasia. He needs supports to convey his physical conditions and tiredness to others. Nevertheless, he cannot recall sometimes any words in his communication due to memory impairment and symptoms of Broca aphasia. As a result, he cannot express his delicate feelings properly by his own voice. He has recovered his communication abilities by his efforts and supports from SLT and his family. He wants to convey his physical conditions and tiredness more properly to others with his delicate feelings or emotions. The second aphasia individual was milder than the first one. He can communicate with others with a little fluent speech, and he has returned to his job by rehabilitation. Therefore, it was less important for him to convey his physical conditions and tiredness to others and to understand physical conditions and tiredness of others. However, he responded that his delicate feelings or emotions could be conveyed to others in his daily life. He also wants to convey more of his delicate feelings or emotions to others by the new design of AAC systems.

#### E. Allocation of the Fuzzy Membership Functions to Convey Delicate Feelings or Emotions

The first aphasia individual did not find the proper words to communicate with others based on his pointed location on the scale before the design. His pointed locations were allocated to the triangular fuzzy membership functions using a survey questionnaire during the design in order to find the proper delicate feelings or emotions when communicating with others. However, his specific position of fuzzy membership functions for corresponding delicate feelings or emotions was not proper. Due to the slope of the triangular fuzzy membership functions, it is possible to change the order of his delicate feelings or emotions based on his pointed location. The change of order of delicate feelings or emotions is done by controlling  $\Delta x$  on the scale. Thus, fuzzy membership functions fit more based on his situation to find proper delicate feelings or emotions during

communication. According to his pointed location, the fuzzy membership functions for physical conditions and tiredness are shown in Fig. 7 and Fig. 8.

He pointed to the delicate feelings or emotions 'very bad' in the first position between bad and usual physical condition. He thought the delicate feelings or emotions 'not really good' and 'pretty bad' in a very close location on the analog scale. The candidates 'not really good' and 'pretty bad' take places respectively after the 'very bad' position. He also thought that 'a little bad' is close to usual condition and thus he pointed it as a neighbor of usual. He thought that 'pretty good' and 'very good' are close and he pointed 'pretty good' and 'very good' respectively on the last two positions. Finally, he pointed the candidates 'fairly good' and 'a little good' after the usual condition respectively.

He pointed to the delicate feelings or emotions 'quite tired' and 'very tired' for tiredness in the first and second place respectively. He then pointed location for the delicate feelings 'a little tired' and 'somewhat tired' almost middle of analog scale respectively. He pointed location on the analog scale for 'not tired at all' in the last position. The delicate feelings or emotions 'Not a little tired' is pointed too close as 'not tired at all'. Finally, he pointed the delicate feeling or emotions 'not too tired' and 'not so tired' far from 'somewhat tired' and near the place 'not a little tired'. He thought that 'not too tired' and 'not so tired' are very close to him to convey tiredness.

#### F. Improvement of Design Solutions

Fig. 9 shows the design of the existing prototype to convey delicate feelings or emotions for physical conditions and tiredness. The existing prototype can be improved by the proposed design as shown in Fig. 10. To improve the prototype, the pointed location is used to support the aphasia participant who wants to convey his delicate feelings or emotions to others. He pointed location on an analog scale to convey his delicate feelings or emotions for physical conditions and tiredness are shown in Fig. 7 and Fig. 8.

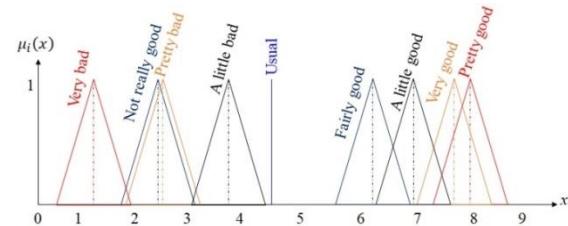


Fig. 7. Delicate Feelings or Emotions in Triangular Fuzzy form to Convey Physical Conditions.

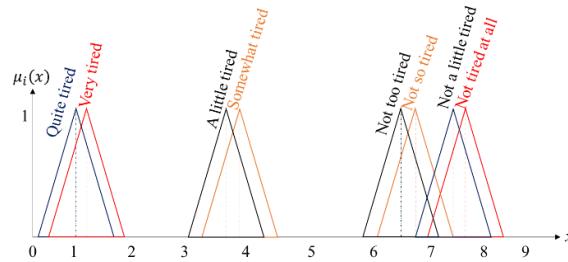


Fig. 8. Delicate Feelings or Emotions in Triangular Fuzzy form to Convey Tiredness.



Fig. 9. Existing Design of Physical Condition (Left) and Tiredness (Right) to Convey Delicate Feelings or Emotions.

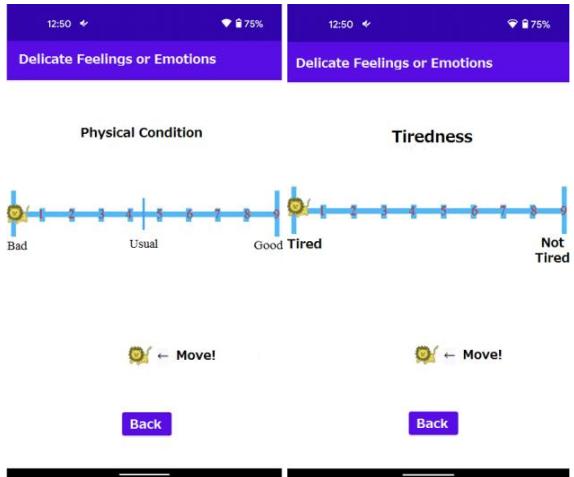


Fig. 10. Proposed Design of Physical Condition (Left) and Tiredness (Right) to Convey Delicate Feelings or Emotions.

The delicate feelings or emotions will be displayed based on the pointed location on the analog scale of the improved prototype for case study as shown in Fig. 11 and Fig. 12. For example, aphasia participant feels 'Pretty bad' and he wants to convey his delicate feelings or emotions to others based on his difficulties. Thus, he points an area between 'bad' and 'good' physical conditions, then the possible candidates of delicate feelings or emotions are selected based on the pointed location as shown in Fig. 11(a). The possible candidates of delicate feelings or emotions and their order are regarded as 'Not really good' and 'Pretty bad' for the pointed area as shown in Fig. 11(a). His desired candidate 'Pretty bad' is placed in the second position on the candidate list. For this reason, he wants to display the list in a more accurate manner. Therefore, aphasia participant moves the pointed location for 'Pretty bad' to  $x+\Delta x$  to adjust his delicate feelings or emotions and the order of delicate feelings or emotions are changed to 'Pretty bad' and 'Not really good' as shown in Fig. 11(b). In this way, he gets the desired delicate feelings or emotions at the top of the list.

Furthermore, aphasia participant feels 'Not too tired' and he wants to convey his delicate feelings or emotions to others based on his difficulties. Thus, he points an area between 'tired' and 'not tired' for tiredness, then the possible candidates of delicate feelings or emotions for tiredness is selected based on the pointed location as shown in Fig. 12(a). The possible candidates of delicate feelings or emotions are regarded as 'Not so tired' and 'Not too tired' for the pointed area as shown in Fig. 12(a). He found that the list of possible delicate feelings or emotions do not have his desired item. Therefore, aphasia participant moves the pointed location for 'Not too tired' to  $x+\Delta x$  to adjust his desire delicate feelings or emotions, the delicate feelings or emotions are changed to 'Not too tired' and 'Not so tired' respectively as shown in Fig. 12(b). Now, he gets his desired delicate feelings or emotions to convey the tiredness.

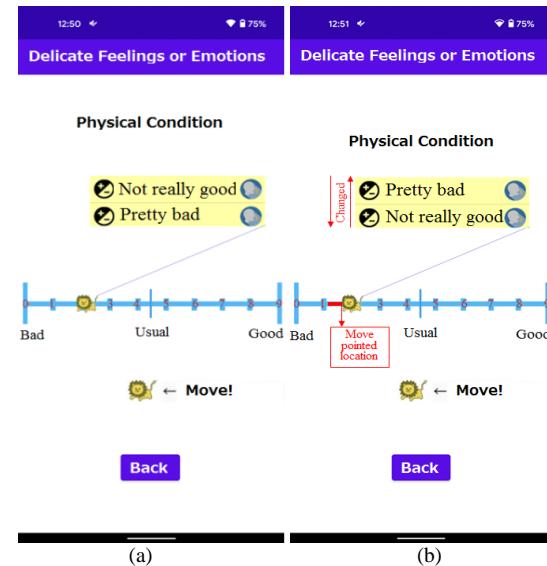


Fig. 11. Adjustment of Delicate Feelings or Emotions for Physical Conditions:  
(a) Conveying Delicate Feelings or Emotion Normally (b) The Delicate Feelings or Emotions after moving the Pointer  $\Delta x$ .

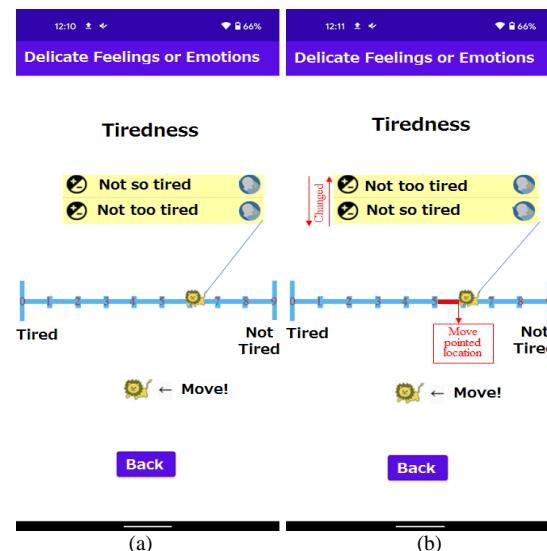


Fig. 12. Adjustment of Delicate Feelings or Emotions for Tiredness: (a) Conveying Delicate Feelings or Emotion Normally (b) The Delicate Feelings or Emotions after Moving the Pointer  $\Delta x$ .

#### G. Evaluation of the AAC systems

In this study, the evaluation was performed by the first aphasia individual who identified the interaction problems and provided his insights for the redesign. In evaluation process, interfaces of the prototype for physical condition after the redesign and before the redesign were provided to the first aphasia individual. We asked his opinions through a survey questionnaire about the improved interfaces after the redesign compared to before the redesign as shown in Table IV.

For conveying delicate feelings or emotions by the first aphasia individual after the redesign, the responses for the questionnaire were collected on a percentage scale (0 to 100). 100% means that he can completely convey and understand the delicate feelings or emotions to participate in society after the redesign. 0% means that his level of conveying and understanding for delicate feelings or emotions did not improve after the redesign.

The questionnaire was designed in two categories. The first category was for the quantitative opinions of the first aphasia individual to convey delicate feelings or emotions for physical conditions. The second category was for the quantitative opinions for understanding delicate feelings or emotions for physical conditions. In addition, open-ended questions were also attached to each question. After collecting his responses, it is easily determined which interfaces can sufficiently useful to convey delicate feelings or emotions.

As shown in Table IV, the first aphasia individual responded that he could properly convey 50% delicate feelings or emotions for the physical conditions to others with the improved interfaces after the redesign compared to before the redesign. He also believed that he could actively participate in society 30% by conveying delicate feelings or emotions to others with the improved interfaces after the redesign. Moreover, he could properly understand 70% delicate feelings or emotions of others with the improved application after the redesign. Furthermore, he thought that others could understand 70% of his delicate feelings or emotions with the improved interfaces after the redesign.

TABLE IV. SURVEY QUESTIONNAIRE FOR EVALUATION OF THE PROPOSED DESIGN OF AAC SYSTEMS AND RESPONSES OF THE FIRST APHASIA INDIVIDUAL

Questions	Responses
How much properly can you convey your physical conditions to others?	I can properly convey 50% delicate feelings or emotions to others
How much more can you actively participate in society by conveying delicate feelings or emotions for physical conditions to others using the improved interfaces?	I can actively participate in society 30% by conveying delicate feelings or emotions to others
How much properly can you understand the physical conditions of others using the improved interfaces?	I can properly understand 70% delicate feelings or emotions of others
How much properly can others understand your physical conditions using the improved interfaces?	Others can understand 70% of my delicate feelings or emotions

#### IV. DISCUSSION

People with aphasia individuals cannot convey their delicate feelings or emotions with the existing design of AAC systems [15-19]. They used the existing AAC systems only for expressing a few words or phrases which cannot be conveyed by them instantly. On the other hand, the experimental result of this study showed that the first aphasia individual can be expressed more delicate feelings or emotions to others using the proposed design of AAC systems. As shown in Table IV, he can convey 50% delicate feelings or emotions for physical conditions with the proposed design of AAC systems because the design of existing prototypes is improved based on his situations. He suffered from Broca's aphasia with the problem of memory impairment caused by two strokes. He can communicate with others, but his speech is non-fluent because he cannot process the languages properly in his brain. Although he could convey his delicate feelings or emotions for physical conditions in some extent to others during communication, his expressions were not understood properly by others. Due to the memory impairment and the language processing problems of Broca's aphasia, he cannot find sometimes any words/proper words in his communication when he uses existing AAC systems. As a result, he cannot verbally express his delicate feelings or emotions properly to others with the existing AAC systems. Using the proposed design of AAC systems, candidate(s) of delicate feelings or emotions were shown based on his specified position  $x$  on the scale. If the candidates were unable to properly express his delicate feelings or emotions, then the function of conveying the delicate feelings and emotions can be realized by controlling the position of the fuzzy membership function from  $x$  to  $x+\Delta x$  or  $x-\Delta x$ . The position of delicate feelings or emotions was difficult to control without the help of Fuzzy-set theory. As a result, the participant can express his physical conditions to others more properly with his delicate feelings or emotions.

The first aphasia individual cannot properly express his own thinking to others because he was Broca's non-fluent aphasia. He had no problems with hearing and understanding, but it was difficult to him to speak the contents of communication. The difficulty of speaking becomes the barrier of his communication before the proposed design. As shown in Table III, he could convey delicate feelings or emotions for physical conditions in some extent with his barrier. Thus, interfaces design for physical conditions using smartphone applications before and after the proposed design have been evaluated. As shown in Table IV, the experimental result showed that the proposed AAC systems design is improved because the participant can convey properly 50% delicate feelings or emotions to others through the proposed AAC systems. This improvement was found after the proposed design because the possible candidate(s) of delicate feelings or emotions were shown using Fuzzy-set theory based on the priority. The order of candidate(s) of delicate feelings or emotions was changed after managing  $\Delta x$  on the scale.  $\Delta x$  was managed so that fuzzy membership function fits more based on his situation. The management of  $\Delta x$  was very helpful to him because it became a supporter for him. Consequently, he can convey 50% delicate feelings or emotions for physical conditions with the proposed design of AAC systems as shown

in Table IV. Therefore, Fuzzy-set theory in design of AAC systems contributed to properly convey the delicate feelings or emotions to others.

## V. CONCLUSION

This study presents the design of an AAC system to convey delicate feelings or emotions for aphasia individuals by the support of Fuzzy-set theory. The design was started from the interaction problems between aphasia individuals and existing AAC systems. To identify the interaction problems, a survey questionnaire is provided to the aphasia individuals in three categories such as conveying delicate feelings or emotions, conveying physical conditions, and conveying tiredness. In addition, an existing prototype of AAC systems is also provided to the aphasia individuals. Moreover, an aphasia individual specified fuzzy membership functions for delicate feelings or emotions as his insights during the redesign. Based on the Fuzzy-set theory, the prototype was improved to convey his exact feelings or emotions to others in daily life. Using the proposed design of AAC systems, conveying delicate feelings or emotions of the first aphasia individual for physical conditions to others can be improved by 50%. As a result, other disabled individuals like him can also convey their delicate feelings or emotions using the proposed design of AAC systems. However, this study investigates how the AAC systems is designed for conveying physical conditions and tiredness with the delicate feelings or emotions to others using Fuzzy-set theory. In the future, other factors will be investigated to apply Fuzzy-set theory at design of AAC systems for conveying delicate feelings or emotions.

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