NoVAGraphS: Towards an Accessible Educational-Oriented Dialogue System

Michael Oliverio[1,*], Margherita Piroi[2,3], Daniele De Giorgi[3], Pier Felice Balestrucci[1,*], Carola Manolino[4,2], Alessandro Mazzei[1,*], Luca Anselma[2,*], Cristian Bernareggi[2], Marina Serio[5], Cristina Sabena[3], Tiziana Armano[2], Sandro Coriasco[2] and Anna Capietto[2]

[1]*Computer Science Department, Laboratory S. Polin, University of Turin, Italy*
[2]*Mathematics Department, Laboratory S. Polin, University of Turin, Italy*
[3]*Philosophy and Science Education Department, University of Turin, Italy*
[4]*Social and Human Science Department, University of Valle d'Aosta, Italy*
[5]*Physics Department, University of Turin, Italy*

Abstract

NoVAGraphS is an ongoing project on educational-oriented dialogue systems, specifically designed to be accessible by visually impaired individuals. The main goal of the project is the design and the realization of *conversational interfaces* for accessing images with an internal graph structure such as UML and E-R diagrams, functional diagrams, and electrical circuits.

At the heart of the NoVAGraphS project lies NoVABOT, a dialogue system for Italian and English based on AIML (Artificial Intelligence Markup Language), an open standard scripting language for dialogue systems. We devised NoVABOT as a web application, implementing a textual dialogue system fully compliant with the Web Content Accessibility Guidelines 2.1, with the aim to allow blind people to use their usual speech-recognition/text2speech interfaces (a *screen reader*). The development of the dialogue system was carried out using an open-source library that was extended with new features to enable the manipulation of mathematical formulas and images.

In this paper we present the main features of the system together with two preliminary evaluations with blind students and teachers who work with visually-impaired students on the specific topic of functional diagrams. These experiments revealed how VIP benefit from using conversational interfaces and how the alternative dialogical representation provided by NoVABOT allows users to explore the diagrams and solve related problems. Moreover, the teachers appreciated the capabilities that such a system could provide students.

Keywords

dialogue systems, inclusive education, accessibility, visual impairment

1. Introduction

The rapid advancement of Natural Language Processing (NLP) can directly benefit the development of systems dedicated for students. In particular, educational Dialogue Systems (DSs) can play the role of a personal tutor for assisting the learning process [1].

In educational settings, ensuring equal opportunities for all students is important. However, Visually Impaired People (VIP) often face challenges in accessing images and graphical structures—such as tables, trees, UML diagrams, E-R diagrams, and circuits—due to inadequate alt-text and image descriptions. Unlike established technologies like tactile and haptic interfaces, which have known limitations [2],

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*Corresponding author.
michael.oliverio@unito.it (M. Oliverio); margherita.piroi@unito.it (M. Piroi); daniele.degiorgi@uniupo.it (D. D. Giorgi); pierfelice.balestrucci@unito.it (P. F. Balestrucci); carola.manolino@unito.it (C. Manolino); alessandro.mazzei@unito.it (A. Mazzei); luca.anselma@unito.it (L. Anselma); cristian.bernareggi@gmail.com (C. Bernareggi); marina.serio@unito.it (M. Serio); cristina.sabena@unito.it (C. Sabena); tiziana.armano@unito.it (T. Armano); sandro.coriasco@unito.it (S. Coriasco); anna.capietto@unito.it (A. Capietto)
http://www.di.unito.it/~mazzei/ (A. Mazzei); http://www.di.unito.it/~anselma/ (L. Anselma); https://www.integr-abile.unito.it/ (T. Armano)
0009-0007-3448-2377 (M. Oliverio); 0000-0002-6519-8383 (M. Piroi); 0009-0001-2161-2263 (P. F. Balestrucci); 0000-0002-8711-4638 (C. Manolino); 0000-0003-3072-0108 (A. Mazzei); 0000-0003-2292-6480 (L. Anselma); 0000-0002-3828-2352 (C. Bernareggi); 0000-0003-2654-7242 (C. Sabena)

Natural Language Processing/Generation (NLP/G) is a relatively unexplored but promising approach for conveying graphical information effectively. The widespread availability of speech-to-text and text-to-speech functionalities in modern electronic devices highlights the potential of leveraging these technologies to reduce accessibility barriers.

NoVAGraphS[1] (Non Visual Access to Graphical Structures) is an ongoing project devoted to the development of educational DSs for VIP that specifically address the treatment of graphical structures. The main goals of the project are: (1) the study and the development of algorithms to convert graphical structures in *dialogue scripts*, that are prototypical dialogue fragments designed to communicate the information conveyed by the graphical structures; (2) the integration of these scripts in educational DSs for VIP; (3) a comprehensive evaluation of these DSs along different perspectives and disciplines.

In [3], we presented both (1) an educational DS designed for English, on the topic of Finite State Automata (FSAEnDS henceforth); (2) a corpus of interactions of humans (6 VIP and 26 non-VIP) with FSAEnDS. FSAEnDS has been designed by using the *happy-paths* User Interaction (UI) methodology[2] and implemented using the AIML (Artificial Intelligence Markup Language) technology [4]. So, the main goals of [3] were the initial evaluation of FSAEnDS by using the standards of accessible technologies and of UI communities.

In this paper we present the main features of NoVABOT, a new DS specifically designed to fulfill the goals of the NoVAGraphS project considering the experience and the results of [3]. There are five new features that empower NoVABOT with respect to FSAEnDS, that are:

- NoVABOT has been realized by accounting **three different domains** (see Section 3.3) related to graphical structures, that are *functional diagrams* from maths, *electrical circuits* from physics, *Finite State Aautomata* from computer science. FSAEnDS considered only the latter.
- NoVABOT has been designed for both **VIP and non-VIP final users**. The idea is to consider the possible users' impairment as just one feature of user modelling. Our assumption is that NoVABOT can be profitably used by different kinds of users that can have (or not have) different kinds of impairments. As a consequence, in contrast to FSAEnDS, the NoVABOT interface is a mix of graphics and texts (see Section 3).
- In NoVABOT, we implemented a procedure for the **automatic creation of interaction scripts** related to the graphical structures. On the basis of the FSAEnDS, where the interaction scripts have been entirely created from scratch by humans using the happy-path methodology, we exploit the vectorial nature of graphical structures. The idea is to convert sub-parts of the graphical structures into *adjacency pairs* of the dialogue script (see Section 3.4).
- NoVABOT has been designed for dialogues in **Italian** (see Section 3), in contrast to FSAEnDS that was designed for English.
- We evaluate NoVABOT by using **pedagogy of mathematics** methodologies. In particular, focusing on the mathematical domain, we collect and analyze the feedback of both (i) 3 VIP students (see Section 4.1), and (ii) 8 specialized teachers on accessible technologies (see Section 4.2). We believe that these two initial evaluations can shed light on the future development of NoVABOT and give a valuable test on the applicability of DSs to the education of VIP.

In the remaining part of the paper, we give a brief report of related work in Section 2, we describe the main features of NoVABOT in Section 3, we report the results of evaluation in Section 4, and finally we close the paper with conclusions and future work in Section 5.

2. Related Works

There are three main approaches in accessible technologies literature for accounting the problem of presenting the information enclosed in graphical structures to VIP.

[1] http://www.integr-abile.unito.it/en/progetto-novagraphs/
[2] http://xunitpatterns.com/happy%20path.html

Haptic representations, that are tactile information as vibration, touch, and force feedback, have been proposed in multi-modal systems for communicating graphical information in several domains as, for instance, graphs [5], chemical formulas [6] and function graphs [7].

Sonification, that is practice of representing data through sound, has been studied in different domains to explore as, for instance, function graphs [8], elementary geometric shapes [9] and maps [10].

Finally, *textual descriptions* of images have been studied for representing, for instance, chemical formulas [11], electronic circuits [12] and function graphs [13].

However, all these studies point out two main limitations of such solutions. First, a strong knowledge of the domain and characteristics of non-visual perception is required on the part of the person making the textual description. Second, the cognitive load to understand the textual description of a complex image is very high since the exploration is strictly *sequential*, without the possibility from the VIP to ask for clarification or repetition of the presented information.

Some academic and commercial works applied NLG to describe to VIP some specific structures, typical of scientific communication. For instance, different NLG techniques have been applied to produce descriptions of bar charts [14], and to the problem of communicating mathematical expressions [15, 16, 17].

Finally, to our knowledge, the only works that use a DS for the specific problem of communicating graphical information to VIP are [3] and [18].

3. NoVABOT Description

In this section, we provide a description of NoVABOT, defining its architecture (Section 3.1), the extension of an open-source library that manages AIML (Section 3.2), the application domains (Section 3.3), a procedure for automatic conversion of a structured image in SVG into AIML (Section 3.4), and, finally, the interface (Section 3.5).

Note that NoVABOT is a web-based and accessible text-based DS that can be accessed by VIP using their own speech technologies, usually a *screen reader* (a dedicated software that reads every item on the screen) and a keyboard. In this way we can evaluate the impact of the dialogic interaction without altering the VIP final physical interaction. Indeed, the use of text-to-speech technologies not specifically designed for VIP can degrade the user experience of VIP users [15, 17].

3.1. Architecture

NoVABOT[3] has been integrated into a web application, developed using a number of standard web library (HTML, JavaScript, Node.js, Bootstrap). The web application follows a typical client-server architecture. The backend, powered by Node.js, manages the business logic, processes user requests, generates responses, and handles conversation logic using AIML. The frontend, which consists of HTML and JavaScript with Bootstrap and EJS, provides an interactive user interface. Bootstrap aids in layout design, while EJS dynamically generates HTML pages based on responses processed by the backend, ensuring a responsive and dynamic user experience. The code of NoVABOT can be found on GitHub[4].

3.2. AIML Library Extension

The development of NoVABOT was carried out using AIML[5], an XML-based language designed for developing DS. More specifically, AIML is a declarative language that follows the pattern-matching paradigm. Rule-based systems, by design, provide consistent and controlled responses, though this comes at the expense of flexibility and scalability.

[3]https://delorean.di.unito.it/novagraph/tre_domini
[4]https://github.com/Reasoning-NLG-Unito/NoVAGraphs_/tree/3domains
[5]http://www.aiml.foundation/doc.html

The AIML-high library[6] was initially used to interpret the AIML files. This interpreter could handle several common AIML tags (Table 1). However, we extended the interpreter by adding some new functionalities described below.

AIML Tag	Description
<bot name="NAME"/>	Defines the name of the bot.
<get name="NAME"/>	Retrieves the value of a variable.
<set name="NAME">TEXT</set>	Sets the value of a variable to TEXT.
<random> - A - B - C </random>	Randomly selects and outputs A, B, or C.
<srai>PATTERN TEXT</srai>	Refers to another category for a response.
<sr/>	Indicates the response should be the same as the request.
<star/>	Represents the wildcard from the user input.
<that>TEXT</that>	Matches the last bot response.
<uppercase>TEXT</uppercase>	Converts TEXT to uppercase.
<lowercase>TEXT</lowercase>	Converts TEXT to lowercase.
<formal>PROPER NOUN</formal>	Formats PROPER NOUN as a proper noun.
<sentence>THIS IS A SENTENCE</sentence>	Outputs "This is a sentence."
<condition name="NAME" value="VALUE"> TEXT </condition>	Outputs TEXT if variable NAME has value VALUE.
<condition> <li name="NAME" value="VALUE">TEXT </condition>	Outputs TEXT based on conditions.
<think><set name="NAME">TEXT</set></think>	Sets a variable without outputting TEXT.
<anyElement/>	Represents any valid AIML element.
<random> <think> <set name="NAME">TEXT</set> </think> </random>	Randomly selects responses, including setting variables.
<random> <srai>PATTERN TEXT</srai> </random>	Randomly selects responses with SRAI pattern reference.
<condition name="NAME" value="VALUE"> <srai>PATTERN TEXT</srai> </condition>	Outputs SRAI pattern based on conditions.
<condition><li name="NAME" value="VALUE"> <srai>PATTERN TEXT</srai> </condition>	Outputs SRAI pattern or TEXT based on conditions.

Table 1
Supported AIML v1.1 tags of the AIMLInterpreter. The tags used within NOVABot are in bold.

Managing Multiple Wildcards This new functionality involved correcting an error in the AIML-highlibrary, where multiple wildcards were not handled correctly. For example, given the pattern: (HELLO * I AM *), which could be triggered by a query like: *Hello Mario, I am John*. It was expected that the interpreter would assign the first wildcard to the string *Mario* and the second to the string *John*. However, the library was erroneously assigning both wildcards to the string *Luca*, indicating a wrong management of the wildcards. The correction ensured that each wildcard was associated with its respective string.

Formula Tag The extension allowed the inclusion of a <formula> tag within AIML templates, enabling the insertion of a mathematical formula conforming to MathJax syntax. The response generated

[6] https://github.com/gleuch/aiml-high

by the interpreter includes any formula detected in the template within \(\), allowing the MathJax library[7] to interpret the formula during the response rendering phase. This capability enhances the NoVABOT utility in academic and technical contexts where precise mathematical notation is crucial.

Image Tag To enable the creation of responses containing images, the interpreter has been enhanced to handle the `<image>` tag. Within this tag, the image name or its path must be specified, depending on how the interpreter's response is handled on the server side. In addition to specifying the image, the `<svgElement>` tag has been implemented, which can be used exclusively for SVG images. With this tag, it is possible to modify the style of an image element by specifying the ID of the element to be modified, the style name, and the value to be applied. An example of an AIML rule using these tags is as follows:

```
<image>functional-diagram.svg</image>
<svgElement
  style-name="stroke"
  style-value="#04ed00">
Mario</svgElement>
```

In this case, activating the rule will return the image name to be rendered and the element to be modified, in addition to the textual response. Specifically, the element with ID `Mario` will be modified, changing the stroke color to green (`stroke:"#04ed00"`).

3.3. Domains

The main goal of NoVABOT is the capacity of answering to questions in Italian related to topics of *functional diagrams, electrical circuits, finite state automata.* To achieve this goal, we focused on designing NoVABOT to understand and process queries in the Italian language.

For the domain of functions, NoVABOT is capable of discussing the fundamentals of set theory, the operations on sets, the types of functions and their properties, and the description of an example function. For the electrical circuits, NoVABOT can assist by answering questions about circuit components, Ohm's Law, and Kirchhoff's Laws, as well as providing explanations about the composition of a sample circuit. Regarding the FSAs domain, NoVABOT provides explanations about the state and transitions of a specific example.

For classifying and managing the users' queries, we use dialogue acts, based on ISO 24617-2 [19, 20], to handle different type of questions. Specifically, we chose `DS:opening`, for the initial greetings, and `Ta:request`, for general questions, such as *Parlami degli automi (Tell me about automata)* or *Descrivimi il circuito elettrico (Describe me the electrical circuit).* For specific questions, like *Quanti stati ha l'automa? (How many states does the automaton have?)* we use `Ta:setQuestion`. Additionally, we use `Ta:propositionalQuestion` for questions that require confirmation or refutation.

We managed theoretical questions by creating AIML rules with a predefined answer for the initial occurrence of each specific question and varied responses for subsequent repetitions. To accomplish this, we utilized an AIML variable to track whether the question had been asked before. For repeated questions, we employed the `<random>` tag, which selects a response randomly from multiple options. This approach was implemented to enhance the system variety when questions are repeated and to provide more comprehensive answers to the user.

For questions regarding specific examples of functional diagrams, electrical circuits and FSA, we built an SVG-to-Text system, which we describe in Section 3.4, to create AIML rules that were subsequently added to the AIML file with the theoretical rules.

3.4. SVG-to-Text

The responses related to domain-specific examples were generated automatically. This was achieved by constructing SVG images for each example (function, circuit, automaton), extracting information from them, and using this information to generate responses for building AIML rules. This process

[7] https://www.mathjax.org/

employed a Template-based system [21]. Although this technique has limitations, such as the lack of flexibility and the inability to handle unexpected inputs, it is suitable for our case, since all diagrams have a strict predefined structure.

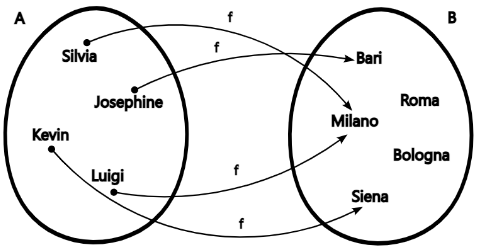

Figure 1: SVG representation of a function used for SVG-to-text extraction.

Consider, as example, the specific function diagram in Figure 1.
By using a simple parser we can extract the relevant semantic information, that is:

```
function
  link-Kevin-Siena
  link-Luigi-Milano
  link-Josephine-Milano
  link-Silvia-Bari
domain(name-A)
  Kevin,Luigi,Josephine,Silvia
codomain(name-B)
  Siena,Bologna,Milano,Roma,Bari
```

With this information, we automatically construct AIML rules. For instance:

`Pattern:` *NOME*DOMINIO*
`Template Schema:` Il nome è domain["name"]
`Filled Template:` *Il nome è A (The name is A)*

The process involved anticipating questions by following the predefined scenarios and building responses using the Template-based Data-to-Text methodology. This approach ensured that NoVABOT can generate accurate and contextually appropriate responses based on the structured knowledge extracted from the SVG representations. The example shows the specific case of the function; the same approach has been applied to circuits and FSA as well.

3.5. System Interface

Figure 2 shows the user interface for NoVABOT, specifically designed for functional diagrams. Various elements were considered to make it accessible for VIPs.

Firstly, the interface is optimised for screen readers—leveraging the familiarity of a tool that VIP are accustomed to due to their personal voice settings (pitch, speed, etc.), with a large input bar and a wide submit button immediately below it.

Secondly, user responses appear below the submit button, and a table at the bottom shows the conversation history, allowing VIP to match questions with answers easily by using HTML tags to navigate the table.

Lastly, the interface includes an image of the structure being navigated. Though accessible via SVG tags, it is meant mainly for future development. Our goal is to expand this tool for supporting individuals with attention deficit hyperactivity disorder, who can benefit from visual aids and color changes highlighting relevant parts.

Note that the web of NoVABOT interface is fully compliant with the Web Content Accessibility Guidelines 2.1[8], thus fully accessible to VIP.

[8]https://www.w3.org/WAI/standards-guidelines/wcag/

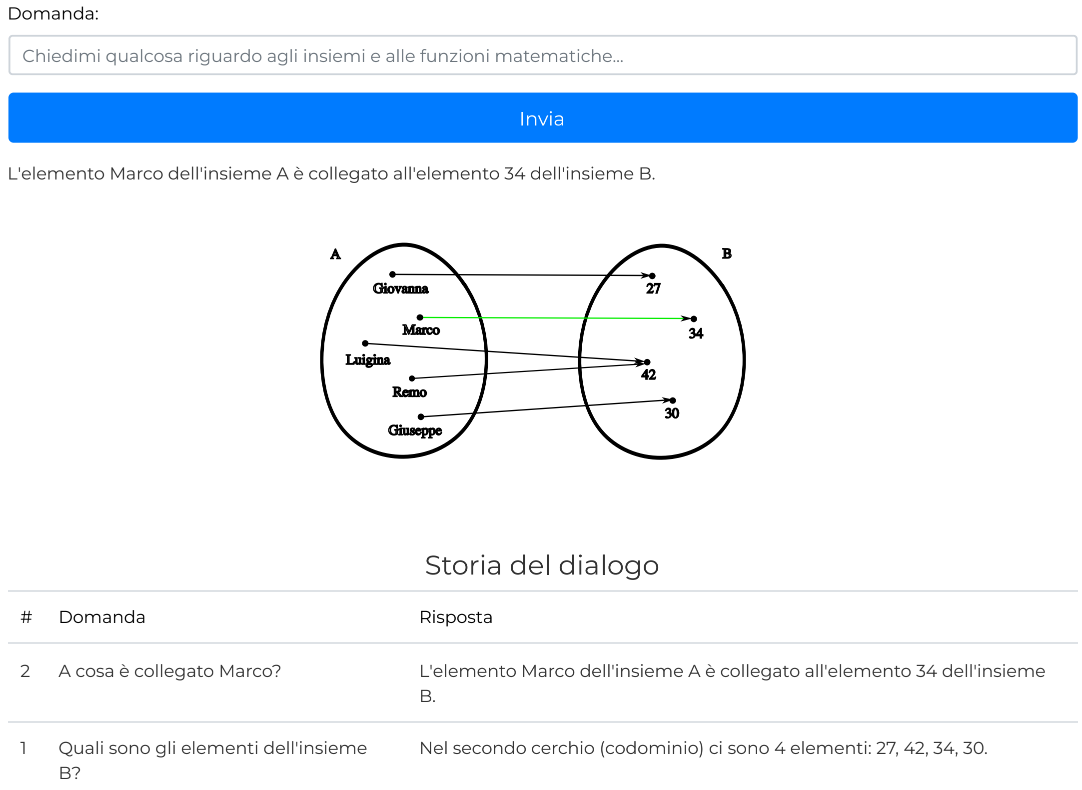

Figure 2: NoVABOT interface for Sets and Functions

4. Evaluation

In order to study the effectiveness of the software for educational purposes, we conducted two different experiments. First, we carried out task-based interviews with blind users to assess the software effectiveness for mathematical practice. Second, we administered and analyzed a questionnaire given to primary and secondary school special education teachers and mathematics teachers.

4.1. Evaluation by VIP

We conducted semi-structured, task-based interviews with three users. Two of them were graduated in scientific subjects and experienced users of assistive technologies, and the third was an undergraduate psychology student. All three users were invited to participate in the experiment on a volunteer basis without compensation.

During the interviews, we focused on the use of representations of functions between finite sets. We adapted a task from [22], where different examples of injective functions were given, followed by different examples of non-injective functions. The interviewed students interacted with NoVABOT to explore the given functions. They were asked to recognize the shared features of the first set of examples and the differences from the second set, ultimately attempting to define an injective function. The same process was repeated for surjective functions. The original version of the chosen example heavily relied on the visual representation of the given functions using Euler-Venn diagrams.

We observed how the alternative representation provided by NoVABOT allowed our interviewees to explore the diagrams and solve the given problems. Specifically, the interviewees confirmed the utility of analyzing different aspects of the function separately by asking NoVABOT specific questions about the number of elements in the domain and codomain or the single connections between elements of the domain and codomain. They then shifted to questions that provided more global information about the function under study allowing its synthetic comprehension.

Nevertheless, the unique representational nature of NoVAGraphS, as compared to diagrammatic graphical representations, implies that, particularly from an educational standpoint, one must be aware that it is not possible to simply “translate” a task represented by a drawing through interaction with the DS. Therefore, instructional design must be sensitive to these differences. For example, interaction times are significantly different, and an “at-a-glance” overview of the diagram under study is still not possible by the user.

We are currently analyzing students' interactions with the software using the Peircean construct of diagrammatic reasoning [23]. This approach aims to deepen our understanding of how students can use this type of auditory representation to understand and utilize diagrams in problem-solving activities. However, all students experienced some difficulties with NoVABOT, as it was unable to answer many of their questions. A crucial aspect of the users' experience regarded the robustness of the natural language understanding (NLU) module in NoVABOT. Indeed, in some cases, NoVABOT was unable to answer some questions posed by VIP. We are currently working on an integration layer with a Large Language Model (LLM) to increase the flexibility of the NLU module.

4.2. Evaluation by Teachers

We also allowed both special education teachers and mathematics teachers from different school levels to interact with the software to assess its usefulness in teaching practices with real or hypothetical visually impaired students.

Eight teachers were invited to participate in the experiment on a volunteer basis without compensation. Each teacher stated that they had experience with at least one visually impaired student. The invitation letter in Italian can be found in Appendix. The teachers were required to interact with NoVABOT for about a dozen minutes and then complete the User Experience Questionnaire (UEQ) [24]. The UEQ calculates six scales: (1) Attractiveness – the overall impression of the product. *Do users like or dislike it?*; (2) Perspicuity – *Is it easy to get familiar with the product and learn how to use it?*; (3) Efficiency – *Can users complete their tasks without unnecessary effort?* ; (4) Dependability – *Does the user feel in control of the interaction?*; (5) Stimulation – *Is it exciting and motivating to use the product? Is it fun to use?*; and (6) Novelty – *Is the design of the product creative?*.

UEQ Scale	Mean	Variance
Attractiveness	0.333	3.89
Perspicuity	1.250	2.78
Efficiency	0.917	3.69
Dependability	1.097	1.42
Stimulation	0.278	3.38
Novelty	0.542	1.94

Table 2
UEQ Scales (Mean and Variance)

Two out of the eight teachers were not included in the analysis of the results because their responses were deemed suspicious (i.e., a problematic data pattern like differing opinions across various scales, or a tendency to always choose the middle category). Table 2 shows the mean and variance results for each scale across the six teachers. Values between -0.8 and 0.8 represent a neutral evaluation, values > 0.8 represent a positive evaluation and values < -0.8 represent a negative evaluation. Given the scale range from -3 (horribly bad) to $+3$ (extremely good) of the UEQ, the observed values are all positive, indicating that NoVABOT performs well in the assessed areas. In particular, the results indicate a generally positive evaluation across most scales, with means above the neutral threshold of 0.8 for Perspicuity, Efficiency, and Dependability. The high variance observed in the results can be attributed to the relatively small number of users.

Given these results, we can conclude, despite the small sample size of teachers who participated in the study, that NoVABOT is expected to be user-friendly, secure, predictable, and effective in its role as a personalized educational DS. However, in order to assess the robustness of this encouraging results, we plan to repeat the evaluation with a larger number of experimenters.

5. Conclusions

This paper reports the study, design, and implementation of NoVABOT, a DS to help VIP to access to graphical structures as functional sets, circuits and FSA. We discussed the system architecture, its interface, and the improvements we made to an open source AIML interpretation library. We proposed a strategy to automatically generating textual descriptions of functional diagrams, electrical circuits and FSA starting from their SVG representation by using AIML rules. Additionally, we conducted two evaluations on the specific domain of functional diagrams: one involving blind students and another with teachers who work daily with VIP. Despite the small number of individuals involved in the experiment, on the one hand, these experiments revealed how VIP benefit from using NoVABOT and how the alternative dialogical representation provided by NoVABOT allows users to explore the diagrams and solve related problems; on the other hand, teachers appreciated the capabilities that such a system could provide to students.

In the future, we plan to collect a corpus of interactions similar to [3] to fine-tune an LLM to overcome the limitations recognized in NoVABOT understanding capacity.

Moreover, we plan to experiment the dialogic platform of NovaBOT in order to explain to the users the graphical constraints of formalizing the diet as a Simple Temporal Problem as in [25] in which the authors explored the use of NLG techniques to educate users about maintaining a healthy diet.

6. Ethical Considerations

During the data collection process, we made sure that all participants in the experiments were thoroughly informed about the research objectives, as well as their rights and responsibilities as participants. Along with the invitation letter, participants received a consent form in which they confirmed, among other things: *i*) to be aware of the objectives of this research; *ii*) to participate on a voluntary basis; *iii*) to be of legal age; *iv*) to be aware that the study was in line with current data processing and protection regulations, on both national and EU level; *v*) to be aware of the possibility of withdrawing from the study at any time, without explanation, without any penalty and obtaining the non-use of the data.

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Appendix A

Invitation Letter

Subject: Invitation to Participate - Testing a Dialogue System for Accessibility of Finite State Automata, Circuits, Functions, and Sets

Dear Colleagues,
We are a research group from the Department of Computer Science and the Polin Lab at the University of Turin.
We need your help to test a dialogue system for exploring finite automata, circuits, sets, and functions. If you decide to assist us, you will interact with a dialogue system that we developed with the aim of improving the accessibility of these topics for visually impaired individuals.

Presentation of the NoVAGraphS Research Experiment
Our research team needs the valuable assistance of people with minimal knowledge of at least one of the following topics: finite state automata, circuits, sets, and functions. We need your feedback to evaluate our dialogue system designed to improve the accessibility of these topics, which are typically taught in courses on Computer Science, Physics, and Mathematics.
The crucial point is that finite state automata, sets and functions, and circuits are generally represented by images that are not accessible to visually impaired individuals. For this reason, we have developed NoVABot, a software that allows visually impaired students to engage in dialogue to understand these topics in an equivalent way.

What to Expect?
Testing the dialogue system: interact with the prototype of the dialogue system using a web interface to explore an automaton, circuit, sets, and functions.
As experts in at least one of these disciplines, explore the software to understand the benefits students may gain from using a customized system.
Complete a questionnaire on Google Forms: we will ask you a few questions to assess the usability and effectiveness of NoVABot.

Interested in Participating or Need More Information to Decide?
To participate or request more information, please contact us at the following email address: pierfelice.balestrucci@unito.it

Sincerely,
NoVAGraphS Research Group