A Review on Assistive Technologies for Students with Dyslexia

Rebeka Lerga
Department of Informatics,
University of Rijeka,
Radmile Matejčić 2, 51000 Rijeka, Croatia
email: rebeka.lerga@inf.uniri.hr

***Abstract* – Last decades have seen tremendous change in education under the influence of the digital technologies. Education no longer relies on traditional methods; it rather makes use of modern technologies. This paper presents an overview of the recent research on the use of assistive technologies in education with emphasis on students with dyslexia, a specific learning disability referred to as a reading disorder which can also affect writing, spelling, speaking and reasoning. The aim of this paper is to provide an overview of the proposed technological solutions as well as the recent research on technologies and methods used to teach dyslectic students language skills, such as reading and writing.**

Keywords – dyslexia; assistive technologies; education, reading assistance, writing assistance

I. Introduction

Difficulties learning to map letters with the sounds of one's language, or to read printed words is often called dyslexia, and is one of the most common manifestations of specific learning disorder [1]. The word dyslexia comes from the Greek words dys (weak or bad) and lexsis (language, word) [2], and like many medical and educational constructs, has definitional challenges [3]. However, the basic notion of dyslexia, described as a difficulty in reading which is often unexpected in relation to other cognitive abilities has reminded constant across most definitions [4] [5] [6]. Moreover, it is most commonly recognized as a specific learning disability that is neurobiological in origin, which primarily affects reading and writing skills, characterized by difficulties with accurate and fluent word recognition, poor spelling and decoding abilities [5] [1] [7], in addition to difficulties in phonological awareness, verbal memory and verbal processing speed [8]. WHO describes it as a specific learning disability marked by specific impairments in information processing which result in difficulties in listening, reasoning, speaking, reading, writing, spelling, or doing mathematical calculations [9].

A. Neurobiological origin of dyslexia

Areas of the brain that process language are highly affected by dyslexia. Since differences have been found in the brains of people with dyslexia [10] [11], experts believe that dyslexia is associated with the left hemisphere and with dysfunction of the brain areas responsible for connecting speech (Wernicke's motor speech area) and voice and speech production (Broca's area). On the other hand, dysfunctions in the right hemisphere create difficulty in word recognition [12]. Moreover, genetic factors are substantially responsible for the familial clustering of dyslexia. The proportion of inherited factors involved in the development of dyslexia is between 40% and 80% [13].

B. Early signs of dyslexia

Dyslexia involves much more than lagging behind in learning to read. The etymology of the name dyslexia expresses the difficulty in using words, how to identify them, what they signify, how they are pronounced and spelled [14]. Students identified with dyslexia have problems in identifying speech sounds and learning how to relate those to letters and words. Moreover, they typically display several key attributes, including: (a) difficulty with word reading, (b) difficulty with spelling, (c) phonological processing difficulties, and (d) slow and laborious reading [3]. Therefore, dyslectic students tend to avoid activities that involve reading; they also show problems in remembering the sequence of the things and most usually are not able to sound out the pronunciation of (more or less) unfamiliar words [15].

C. The prevalence of Dyslexia

Experts have estimated that 5-10% of school-age children fail to learn to read in spite of normal intelligence [11], and 10% of the population (or up to 20% depending on definition), suffer from such condition [11] [16].

According to the Croatian Dyslexia Association, it is estimated that 10% of the Croatian population has some form of dyslexia that creates problems in schooling [17]. In the school year 2019/2020 in Croatia, 314148 students attended primary school [18], therefore about 3100 children needed help to overcome difficulties and successfully attend school.

In addition, there are other disorders similar to or related to dyslexia, including developmental auditory imperceptions, dysphasia, specific developmental dyslexia, developmental dysgraphia, and developmental spelling disability [3], in fact, reading disability is by far the most common learning disability, affecting over 80% of those identified as learning disabled [4].

Being a life-long condition, early identification and treatment of dyslexia are associated with improved outcomes academically and quality of life [3]. Therefore, dyslexia has been the focus of considerable interest for transdisciplinary studies, trying to develop rational and effective therapy to enable successful outcome.

II. TECHNOLOGY ASSISTED EDUCATION

This paragraph presents a literature review of the recent research on the use of technology for students with specific learning disorders, with an emphasis on technologies that are either specifically designed for, or have the features that can be useful for dyslexic students. In this paper these technologies are classified according to the type of devices they are mainly intended for. First paragraph presents desktop software, while second deals with mobile applications. In addition, proposed solutions, which were not yet evaluated by users, are presented within the third paragraph.

A. Desktop Software and Applications

There is a wide range of software specifically designed to assist people with leaning disorders, including dyslexia. Most of such software is directed towards enhancing reading and writing skills. For such cause was developed the Phonological Awareness Educational Software (PHAES), which presents a hypermedia application for helping dyslexic readers, using phonological awareness training in Greek language (Figure 1).

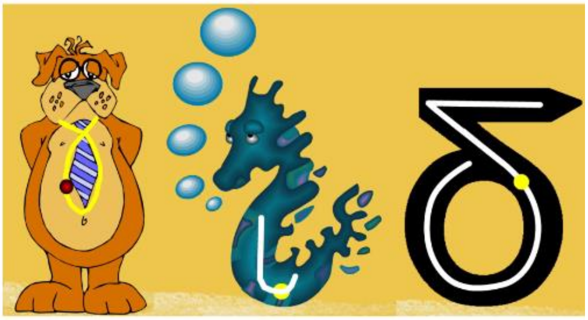

Figure 1 Example of PHAES interface (Source: [19])

Learning activities present graphemes and corresponding phonemes at the word and sentence level. The PHAES demands only basic computer skills, it is designed with simple graphics and navigation, and is therefore suitable for young learners who can use it with or without supervision. It can be supportive tool for both teaching and speech therapy treatment, and it uses multisensory approach. Moreover, it consists of four phases and tasks are divided according to difficulty. The first stage deals with practicing letter-sound correspondence, in the second stage letters are embedded into words, the third stage introduces sentence formation and in the final stage students are asked to form common words. The software has proved to be educational in early literacy development, moreover participant were motivated and found it easy to use [19].

The following study [20] examined the experiences of two groups of students with dyslexia using two different software programs specifically developed to support students with learning disorders. The first program, Kurzweil 3000, a comprehensive reading, writing, and learning software for students with special needs, served as a text reader (text –to-speech software) with embedded study and writing skills localized for the Dutch language. The other one, Sprint, served as a comparable program that added speech and language technology to a computer. In other words, Sprint read the text aloud while and after it was entered. The results showed that, even though assistive software could facilitate learning to some extent, there were other preconditions that needed to be in place to successfully implement software in learning process, such as availability of digital course material, the possibility/authorization to use ICT during classroom courses and assessments, and sufficient training for students to fully use all the possibilities these assistive technologies offered. In addition, another research [21] also used Kurzwiel 3000 as a text-to-speech software to investigate whether orthographic learning could enhance the reading skill for dyslexic children. Effectiveness of the software was analyzed using the phonological recordings. In their study, 65 dyslexic children were asked to read eight stories containing embedded homophonic pseudoword targets in Dutch language (e.g. Blot/Blod, Kowand/Kowant). Participants read stories with and without assistance of the software and subsequently were assessed based on their completion of naming, spelling and orthographic-choice task. This study showed that children with dyslexia can obtain orthographic knowledge through independent silent reading, therefore target spellings were correctly identified more often, named more quickly, and spelled more accurately than their homophone foils. However, a negative effect of text-to-speech software on orthographic learning was demonstrated among younger students who only passively listened to the auditory presentation of the text, because dyslexic students needed to participate in active reading to enhance their reading skills [22].

Moreover, another research [23] showed that generic e-learning applications are not as effective with dyslexic learners because what might be required are specific learning applications that are tailored for specific categories, depending on the dyslexia type. Experimental study [24] presented the same point using a novel dyslexia adaptive e-learning management system (DAELMS) (Figure2).

Figure 2 Leraning materials implemented in DAELMS (Source: [24])

The system correlated each given dyslexia type with its preferred learning style, and subsequently adapted the learning materials which are presented to the student. Being an adaptive e-learning system, the DAELMS incorporated several personalization options: (a) navigation, (b) structure of curriculum, (c) presentation, (d) guidance, and (e) assistive technologies that ensured that the learning experience is aligned with the user's dyslexia type as well as the preferred learning style. The DAELMS was evaluated by the group of university students studying a Computer Science related majors. The participants were presented with course materials related to their field of study (Computer Science). The evaluation results proved that when the system provided the user with learning materials that matched their learning style or dyslexia type it enhanced their learning outcomes.

Another team of researchers [25] developed a Strategic Reader, technology based system that incorporated curriculum based measurement (CBM) and a universal design for learning (UDL) aiming to enhance the reading skills of students with learning disabilities. The CBM presents a form of formative assessment, used to monitor student growth, evaluate performance, and change instruction. On the other hand, the UDL is a framework for instructional design, based on scientific insights into how humans learn, which is supportive for all learners, including those with learning disabilities. It is based on three principles: (a) to provide multiple means of representation, (b) to provide multiple means for action and expression, and (c) to provide multiple means of engagement for students. In addition, the Strategic Reader was created with three components: (a) the CBM to monitor the students' progress, (b) an online forum for discussion, and (c) an interactive, computer-supported reading environment. The participants were 10 teachers, 307 middle schools' students in total, with 64 students identified as those with learning disorder. Teachers who participated could easily create interventions for students due to the flexibility of the tool. The effectiveness of Strategic Reader was evaluated using two treatment conditions for measuring progress (online vs. offline). Using both quantitative and qualitative data analysis, results showed that students using the online tool experienced significant growth in comprehension scores. Moreover, the difference in score growth in the online versus offline conditions was especially large for students with learning disabilities, who experienced a statistically significant score increase in the online progress monitoring condition. In addition, students with learning disorder were significantly more engaged by (and with) Strategic Reader, finding many aspects of the tool more helpful than other general education students.

B. *Mobile Applications and Games*

In addition to computer software, more recent studies are directed towards the design of mobile applications for educational purposes. The following research was conducted using the "Dyslexia Baca", interactive mobile application (in Malay language) designed to enable students to practice the difference between perceptually similar letters (p / b / d and m / w). The application was based on multisensory approach and intended to assist alphabet recognition for dyslexic children. Initial research has shown positive results, the students found the application interesting, easy to use, and a good support for learning [26]. In addition, playful and targeted exercises can be used to improve the language skills of children with dyslexia. Therefore, the following study [27] was conducted using iLearnRW software (Figure 3), developed to provide individualized intervention through games.

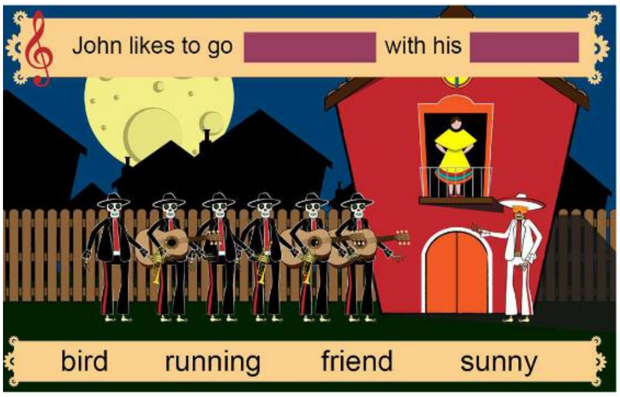

Figure 3 Game activity example: Serenade hero (Source: [28])

The software incorporated learning activities, derived by dyslexia experts, that especially addressed language areas that were most challenging for dyslexic students. The game consisted of two modules: a student model and a lesson planner. Individualized intervention was provided through an underlying user profile, which incorporated language features and was constantly updated as the student played games. For each difficulty, the model kept track of the student's skill based on their performance during game activities and the time elapsed since the last practice. The software selected language material based on student's difficulties and progress. The participants were 78 dyslexic students, aged between 9 and 11 years old. After the 6-month intervention, the students were assessed in order to establish the tool's effectiveness. The results' analysis revealed that there was a strong constructional linkage between the profile entries of the sample, the language content of the tasks of the screening test as well of the games and its effectiveness in the students' performance. In addition, the students who received specific guidance by their teachers, obtained higher success rates in most of the games than those without any guidance.

To improve the educational performances of students with dyslexia, the authors of the following study [29] developed a multimodal, cloud based, mobile learning tool. It provided convenient data input and output and was adaptable to fit each student's profile and preferred learning style with a multimodal function that was provided in different formats (images, audio, and text). Learning materials were created based on approved pedagogical standards. Also, students were able to interact with content through different modes. Authors conducted a user needs analysis through a literature review, interviews and questionnaires with special educational teachers, dyslexic students and their parents, and offered the architecture with three components: (a) a mobile client, (b) a public network, and (c) a cloud environment to provide the content. The results of this study revealed that the multimodality function supported the needs of students with dyslexia, enhancing their learning progress by almost 30%. The evaluation was presented using a pretest-posttest design showing an increase in reading skills after three months of use. In addition, results showed that the user-friendly interface has positive impact on students' motivation to use the tool. Moreover, interesting, and appropriate presentation of learning materials eliminated boredom and provided helpful mechanisms to aid students' reading ability.

Another interactive mobile application, “EasyLexia” (Figure 4), was developed with the aim to improve dyslexic students' fundamental skills, such as reading comprehension, orthographic coding, short-term memory and mathematical problem-solving using gamification approach.

Figure 4 EasyLexia: Main page layout (Source: [16])

The application was developed for both mobile phones and tablets and was tested among students at a “Speech Therapy Center”, located in Syros Greece; however, the application was designed in English language. Preliminary evaluation of this application with 5 dyslexic students (aged 7 to 12) showed promising results in such contexts as the students showed progress in performance over a short period of time. In addition, results indicated that tablet applications aimed for children with dyslexia, could potentially be more engaging than mobile devices [16].

Another research [30] integrated teaching materials in an iPad game, DysEggxia (Figure 5). In contrast to previous approaches, these exercises (in Spanish language) presented the child with a misspelled word as an exercise to solve. These training exercises were created based on the linguistic knowledge extracted from the errors found in texts written by children with dyslexia. To test the effectiveness of this method in Spanish, the study was carried out for eight weeks, 48 children played either DysEggxia or WordSearch, another word game. The children who played DysEggxia for four weeks in a row had significantly less writing errors in the tests than those playing WordSearch for the same time. The results provided evidence that error-based exercises presented using tablets helped children with dyslexia to improve their spelling skills. Moreover, it proved that technology in order to be useful in education must integrate right didactic and pedagogical methods.

Figure 5 Dyseggxia: derivation exercise (left) and substitution exercise (right) (Source: [31])

The following research [32] presented Picaa (Figure 6), again a mobile platform for iPad and iPod devices, specifically tailored to special learning needs. The system was designed to cover the main phases of the learning process: preparation, use and evaluation, and included different learning exercises, such as sorting, associations, puzzles, and exploration. Teachers could adapt the interface and contents of exercises and activities to meet the educational needs of each student.

Figure 6 Picca interface (Source: [33])

The participants in the study were 39 elementary school students with learning disorders (including dyslexia) and the evaluation was based on pre/post testing. The results showed that the use of the learning platform Picaa was associated with positive effects in the development of learning skills such as language, math, environmental awareness, autonomy and social awareness. Also, in many cases students had the opportunity to perform activities that previously were not accessible to them due to the interface and contents. Moreover, the use of electronic devices and multimedia contents increased their interest in learning and attention [32]. In addition, another research has been conducted on the use of iPad computerized instruction system for 35 students (10 - 15 years of age) with dyslexia, dysgraphia, speaking and writing disabilities. This system consisted of eighteen 2-hour lessons with different learning exercises to enhance spelling, handwriting, and sentence composition (syntax) by engaging all four language skills. The results showed improvements in spelling, and both oral and written syntax construction. The computerized writing instruction transferred to better writing with pen and paper. Moreover, performance during instruction on specific learning activities correlated with writing outcomes; and individual students tended to improve in the impaired skill associated with their diagnosis [34].

The following case study [35] analyzed the effect of badges on the engagement of students with special educational needs (including dyslexia) in educational process. Authors used a badge-based gamification strategy for an academic course through Moodle, a learning management platform. The authors interviewed five students and analyzed data from the Moodle platform. The results showed that students perceived the gamified version more interesting and motivating; and were able to concentrate for much longer than usual.

In addition, another learning model LexiPal [36] (Figure 7) integrated educational gamification approach for dyslexic children, by incorporating seven gamification elements, namely (1) story/theme, (2) clear goals, (3) levels, (4) points, (5) rewards, (6) feedback, and (7) achievements/badges.

Figure 7 LexiPal: Example of gamified learning (Source: [36])

The game elements were used with a purpose to encourage dyslexic students while granting desired psychological outcomes when they used the application, including engagement, enjoyment, and motivation. The participants in the study were 40 dyslexic students, and the application was evaluated using qualitative and quantitative approach. Based on the observation while students were using the application, it showed that gamification increased their interest in using the application, most of the students were eager to participate in the evaluation process until it was ended, thus the gamification improved engagement of dyslexic students. On the other hand, quantitative analysis showed that all students enjoyed playing, and most of them wanted to play it again, which indicates that gamification can improve enjoyment and motivation of the children. However, the results are considered as a short-term effect, which is the effect of gamification when and after dyslexic children used the application in short duration (45 minutes) [36].

Moreover, another paper explored potential benefits of gamification for a specific dyslexic population, students with dyslexia who were transitioning from primary to secondary school. The classDojo, a gamification platform, was adapted for the dyslexic students by teachers from dyslexia teaching center. It was used for twelve 1.5-hour lessons. Two main components of the classDojo system were emphasized for this study: (1) awarding of badges, and (2) the reporting system. The teacher could award a badge from a set list of either positive (green) or negative (red) badges. The set of badges was fully customizable for each teaching session, allowing the teacher to tailor the awards for the needs of their students. On the other hand, the report system maintained a record of the badges awarded. Moreover, a report of a child's badges was automatically emailed to parents every week, as well as comments teachers had written about specific badges. The authors collected data by means of interview (with teachers, students, and parents) and kept daily log of students' and parents' logins to the application. The results indicated that gamification can foster student motivation, in this instance, due to an interaction between a highly customizable design as well as pedagogically tailored appropriation by teachers [37].

In addition to games and educational applications, recent years have seen the practice of using social media platforms to enhance both formal and informal learning. Moreover, they have been used in education for students with specific leaning disorder such as dyslexia. The following study [38] was conducted using Facebook. In a five-week study, 60 dyslectic students participated in a research in which a group Facebook page was constructed for five 90-minute weekly sessions. Researchers used different methods for data collection such as participant-observation, interviews, video, and dynamic screen capture. Results of this study suggested that digitally mediated social networks have the potential to make education more equitable for such students. Dyslexic students saw Facebook as a very useful tool in their education, besides supporting inclusion, it helped in keeping up to date and meeting deadlines, having increased control over learning, developing metacognitive awareness, and enabling greater control over literacy process and demands. Moreover, most of social media platforms are rich in multimodality. However, Facebook is mostly driven by reading and writing, therefore it might be anticipated that dyslectic students would find it problematic to use. The evidence from this study suggested that, contrary to any such expectation, participants were very highly motivated to use Facebook for learning literacy.

C. Proposed educational systems

There are several proposed solutions developed for students with specific leaning disorders. This paragraph presents an overview of several proposed applications, developed to provide writing and reading assistance for students with dyslexia.

The following application, DYSLEX_RE, was proposed as a solution to enhance reading skill for dyslexic readers. It is a real-time reading assistant application which uses Google's mobile vision API & OCR, and therefore provides real-time facility. The detected text is displayed to the user in OpenDyslexic, a free font designed to avoid some of the common reading errors caused by dyslexia. This application uses multisensory approach providing suitable learning environment for dyslexic children [39].

The following research [40] proposed text-to speech engine in a multimodal learning and communication system for children with learning disabilities. The proposed system is user-friendly, portable, and easy to maintain, a Java-based Android application for mobile devices. The system consists of a GUI that includes categorized pictures and a keyboard. The moment user clicks on an image, the system sends the image to a phrase library to convert it to text. Afterwards, the text-to-speech engine processes the text and produces a sound as output. In other words, the primary goal is to allow dyslectic students to get sound stream output from the images or text given as input. Moreover, users can build sentences from the images they select from the given categorized image directory. Also, users can upload more pictures and match them with existing words, phrases or add new meanings to the uploaded images. However, as of now, all speech generated by the proposed system is handled in the English Language.

Another team of researchers [41] proposed an assistive learning environment framework to enhance the learning processes of students with learning disabilities (including dyslexia). To gain information about students' needs, authors visited special institutions and hospitals as well as interviewed special education teachers. The proposed framework consists of a web-based environment including content repository to store the materials, a learner profile to store the learner's personal information and learning goals, an assistive learning engine (which adapts the content to each learner) and, in addition, a monitoring module providing teachers and parents with updates on learner progress. Even though, the proposed framework is based on a comprehensive architecture that is adaptable to each student's learning style, it is restricted to a specific location, and does not support multimodal interface. Multimodal approach was neglected in the following study [42] as well. The authors proposed a mobile intelligent tutoring system (ITS) for students with specific learning disorders aiming at teaching all four language skills. This proposed system is based on the Android platform, combining OSGi features and semantic web technologies, and provides mobility, context awareness and adaptability.

Furthermore, some of the proposed systems integrated specific pedagogical approaches. The following study [43] used Orton-Gillingham (OG) instructional approach to develop an application called “Dyscover”, a HTML5-based application that takes into account most aspects of modern technologies, such as touch-screens, accelerometers, gyroscopes, voice recognition, and sound reproduction. All these aspects correlate with implementation of multisensory approach, in the application suited for language learning by dyslexic students and pre-school children. Moreover, the research presents personalization of the Orton-Gillingham approach using Gardner’s theory of multiple intelligence. Firstly, according to users’ response to the questionnaire, the application is personalized in terms of used color, sound, or other forms of audio-visual-kinesthetic elements more suited to the type of intelligence that the user is stronger in. Then, the application directs towards explicit, multisensory, structured, and prescriptive way to teach literacy in line with the pedagogical approach, with the idea of replacing a one-to-one teacher-student instructional model.

However, all the systems proposed in this paragraph are in its initial stages and have not been tested among the users. Nevertheless, they present an insight in current studies towards developing an educational tool that could be used by dyslexic students to help enhance their writing and reading skills.

III. RESEARCH ON DYSLEXIA IN CROATIA

Moreover, several researches were conducted among teachers in order to determine their attitudes towards the use of technology in classroom with dyslectic students. The following research [44] presents Croatian teachers' perception towards the use of ICT. The participants were 35 Croatian speech and language pathologists (SLP) who expressed their attitudes towards possibilities of ICT use in practical work with dyslexic students. The results showed that the respondents were highly aware (M = 4.49) of the benefits of using ICT and had a very positive attitude towards using ICT in practical work. Moreover, respondents used ICT significantly in preparation for work (94.3%) and to a slightly lower level (60%) for working directly with students.

There are several educational applications developed and designed in Croatia for students with learning disorders and specifically for students with dyslexia. One of the recently developed applications is OmoReader, with the OmoType, highly readable font designed within the application, which can be adapted to the individual needs of users. In addition, the application allows words to be broken down into syllables using the automatic syllabification procedure for the Croatian language [45], which helps users to read more correctly (Figure 8). Users can also insert lines in the background of the text to make it easier to follow the text, which helps in staying focused and keeping the reading speed. Within this application, users can also access 200 Croatian books, enriched with 3D content, animations, videos, audio, images, and comprehension tasks. The application also supports OCR technology, which recognizes text from various sources, printed and digital. Also, users can convert, edit and save texts using the camera on a mobile device by capturing texts from books, magazines and others printed forms. In addition, data obtained from users is used solely for the purpose of analysis required to develop and improve the application [46].

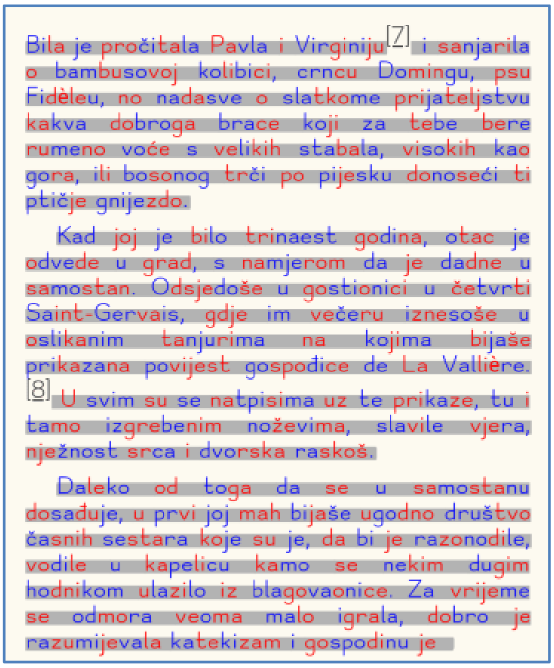

Figure 8 OmoReader interface (Source: [47])

Several other applications, adapted to the specifics of the Croatian language, were designed and developed within the project named Competence Network for Innovative Services for Persons with Complex Communication Needs (ICT-AAC), a multidisciplinary project focused on ICT based augmentative and alternative communication. Different experts worked together to create iOS and Android applications, including several specifically designed for dyslexic students, such as Letters, Vocals, Memory, Learning Syllables, Learning Words, Learning to Read (Figure 9), and Language Builder. These applications can be used for direct speech therapy for students with dyslexia, for developing phonological awareness and morphological skills, as well as initial writing skills for young learners. All ICT-AAC applications are visually attractive, provide multisensory access to learning (tasks are accompanied by visual and auditory support, different syllables are highlighted in different color) and often give positive feedback for correct task completion, which is essential for a sense of success in students with dyslexia [44].

Figure 9 ICT-AAC Learning to Read interface (Source: [48])

IV. FUTURE WORK

Table 1 presents an overview of the above mentioned assistive technologies for dyslexic students. Even though all these applications and software are very useful, there is still room for improvement, which is the aim of our future work. Moreover, current technologies need to be further analyzed with the emphasis on their main features, such as interactivity, multimodality, simple graphics and navigation, personalization elements, gamification, and other features considered as important for dyslexic students. In addition, future analysis of assistive technologies implies development of a conceptual model for a system that would support educational processes (both teaching and learning) for dyslexic students.

V. DISCUSION AND CONCLUSION

Dyslexia, namely characterized as reading disorder, affects around 10% of population, and is therefore one of the most common learning disorders. It mostly affects language skills that involve reading, spelling, and writing. However, it is not linked to intelligence, or, in other words, dyslexic students' cognitive abilities do not differ from those of their peers, even though they lag behind when it comes to developing language skills, and mainly reading comprehension. As such, reading comprehension is described as the ability to grasp or fully understand information communicated through text. Therefore, dyslexic students mainly lack the ability to comprehend written texts. Moreover, dyslexia has been the focus of considerable interest from researchers in different areas, including neurophysiology, linguistics, educational sciences, computer science and others.

The explosive growth of digital technologies and developments in artificial intelligence have provided powerful possibilities for developing educational aids for students with learning disorders. Also, m-learning, and e-learning have become an influential trend in the educational process. New educational trends promote learning accessibility and flexibility. Moreover, there are additional aspects of these educational trends, as well as assistive technologies, that are especially useful for the students with dyslexia. This paper presents an overview of recent research on the use of technology to assist students with learning disorders, and specifically with dyslexia, both in formal and informal education.

Although there is a substantial amount of research, and applications available for students with dyslexia, there are several gaps that must still be addressed. Firstly, most of available applications are directed towards the enhancing of language skills for native languages. Moreover, applications are mostly in English language, designed for students' whose native language is English. Therefore, there is a little research on how dyslexic students acquire foreign languages, in terms of developing all language skills in English as a foreign language, and furthermore, what are the implications for developing such learning system for dyslexic students whose native language is Croatian.

Another substantial issue pertains to the lack of a comprehensive learning system which would be directed towards enhancing all language skills (reading, writing, speaking and listening). Available applications and software manly emphasize either reading or writing skill and neglect the language comprehension, as a whole. Moreover, educational systems are usually created and designed with the aim to help dyslexic students, however, little number of applications is used after the research. Even though the assistive technologies prove to be useful, and increase students' motivation and self-confidence, in most cases, after the research is over, the teachers and students return to previous educational model.

Moreover, it is not enough for technology to exist in the classroom, it is only beneficial when used appropriately. Thus, effective educational methods must comply with pedagogical requirements. Due to interactive aspect of education, learners should be more involved in the learning process. Therefore, digital technology, used in education, must offer students autonomy with attention to their age, special educational needs, potentials, and preferences. Also, not all methods and technologies are appropriate for all students. They have to match individual's learning style. Moreover, since all dyslexics do not share the same symptoms, each student presents a special case when adopting educational tools. Therefore, there is a strong need to involve individualized approach when developing assistive technology for students with dyslexia.

In addition, effective educational systems for dyslexic students support multisensory approach, which is crucial for improving students' reading skills. In such approach, the same information is presented in different formats (text, image, sound, and other) since students learn best when they use all senses. Moreover, collaborative learning presents another virtue of assistive technologies. In addition to one-on-one learning, technology enables students to collaborate with one another, with teachers, parents, tutors, and other individuals. Collaboration gives students the sense of integration, which is very important for all students, and especially for those with learning disorders.

Furthermore, learning environment needs to be interactive, filled with instructional resources and challenging assignments, enabling students to become engaged participants. Thus, games have become a very effective educational aid for dyslexic students, especially because they use badges (rewards) and points (ranking). These offer a constant feedback and promote competition, which is a highly motivating factor.

After all, new technologies offer a wide range of possibilities for development of educational aids for dyslexic students. They open new avenues through which students with dyslexia can learn and enhance language skills, both in their native and foreign language.

Table 1 Available assisitive applications for dyslexic students

1) DESKTOP APPLICATIONS					
Name	**Main features**	**Evaluation type**	**Number of participants**	**Educational environment**	**Reference**
PHAES	Interactive, multisensory, user-friendly navigation, display difficulty levels	Empirical study – observation and interview	5	Formal and informal	[19]
Sprint	Text-to speech, partially personalized (users can chose texts)	Empirical study – three surveys (during the academic year)	15	Formal and informal	[20]
Kurzweil 3000	Interactive, text-to-speech, spelling-checker, word prediction, translation (powered by Google Translate), bookmarks, text and audio notes, personalized	Empirical study – analysis of phonological recordings in addition to naming, spelling and orthographic-choice tasks	65	Formal and informal	[21]
DAELMS	Incorporated personalization options, adaptive (materials presented to students aligned with dyslexia type and learning style)	Experimental study	48	Formal and informal	[24]
Strategic Reader	Interactive, multisensory, incorporated curriculum based measurement, applied universal design for learning	Experimental study	317 (10 teachers, 64 students with learning disorders, 243 other students)	Formal and informal	[25]
2) MOBILE APPLICATIONS					
Name	**Main features**	**Evaluation type**	**Number of participants**	**Educational environment**	**Reference**
Dyslexia Baca	Interactive, multisensory, rewarding system, user-friendly interface, incorporated difficulty levels	Heuristic evaluation (7 experts in the aspects of content, approach, support, multimedia elements, user friendliness)	7 (experts)	Formal and informal	[26]
iLearnRW	Interactive, individualized approach (learning materials	Experimental study	78	Formal (under supervision) and informal	[27]

	selected based on student's difficulties and progress), multisensory, gamification elements			(without specific supervision)	
Multimodal interface tool	Interactive, multisensory, cloud based, personalized (output aligned with student's profile and preferred learning style)	Experimental study	NA (random number)	Formal and informal	[29]
EasyLexia	Interactive, multisensory, user-friendly interface, gamification elements	Experimental study	5	Formal and informal	[16]
DysEggxia	Interactive, multisensory, user-friendly navigation, gamification elements, included error-based exercises	Experimental study	48	Formal and informal	[30]
Picca	Interactive, multisensory, personalized (interface adapted to each student's needs), incorporated teaching preparation, presentation and evaluation	Experimental study	39	Formal and informal	[32]
iPad computerized instruction	Interactive, multisensory, incorporated exercises for spelling, handwriting and syntax	Experimental study	35	Formal and informal	[34]
Moodle	The study focused on gamification approach and used badge-based strategy	Empirical study – interviews and data collected from the system	5	Formal and informal	[35]
LexiPal	Interactive, multisensory, gamification approach	Empirical study – observation and survey	40	Formal and informal	[36]
ClassDojo	The study focused on gamification approach using badges and reporting system, adaptable design	Case study	9 (2 teachers and 7 students)	Formal and informal	[37]
OmoReader	Personalized (preview adapted to students' needs), involved syllabification approach for Croatian language, OCR technology	NA	NA	Formal and informal	[46]
ICT-AAC applications	Interactive applications developed for different language areas, multisensory, user-friendly visuals, feedback	NA	NA	Formal and informal	[44]

REFERENCES

[1] American Psychiatric Association, Diagnostic And Statistical Manual Of Mental Disorders, 5th ed., Washington, DC: American Psychiatric Publishing, 2013.

[2] Hrvatska udruga za disleksiju, "Definicije disleksije," hud.hr, 2014. Retrived from: http://hud.hr/definicije-disleksije/, [Accessed: 10 June, 2020].

[3] G. Stoker, K. Drummond, C. Massengale, C. Bahr, S. Lin and S. Vaughn, "Dyslexia and Related Disorders Reporting Study," American Institutes for Research, Austin, Texas, 2019.

[4] S. E. Shaywitz, R. Morris and B. A. Shaywitz, "The Education of Dyslexic Children from Childhood to Young Adulthood," Annual Review of Psychology, vol. 59, 2008, pp. 451-475.

[5] G. Lyon, S. Shaywitz and B. Shaywitz, "A definition of dyslexia," Annals of Dyslexia, vol. 53, 2003, pp. 1–14.

[6] American Psychiatric Association, Diagnostic and Statistical Manual of Mental Disorders, 4th ed., Washington, DC: American Psychiatric Press Inc, 1994.

[7] British Dyslexia Association, "What is dyslexia," www.bdadyslexia.org.uk, 12 February, 2020. Retrived from: www.bdadyslexia.org.uk/dyslexia/about-dyslexia/what-is-dyslexia, [Accessed: 10 June, 2020].

[8] J. Rose, Identifying and Teaching Children and Young People with Dyslexia and Literacy Difficulties, Nottingham: DCSF Publications, 2009.

[9] World Health Organization, World Report on Disability, Malta: WHO Press, 2011, p. 309.

[10] J.-F. Démonet, M. J. Taylor and Y. Chaix, "Developmental dyslexia," The Lancet, vol. 363, issue 9419, 2004, pp. 1451-1460.

[11] M. Habib, "The neurological basis of developmental dyslexia: An overview and working hypothesis," Brain, vol. 123, issue 12, 2000, pp. 2373–2399.

[12] MSD, "MSD priručnik dijagnostike i terapije pod pokroviteljstvom Hrvatskog liječničkog zbora", www.msd-prirucnici.placebo.hr, 2014. Retrived from: www.msd-prirucnici.placebo.hr/msd-prirucnik/pedijatrija/razvojni-poremecaji-i-poremecaji-ucenja/disleksija, [Accessed: 15 May, 2020].

[13] J. Schumacher, P. Hoffmann, C. Schmäl, G. Schulte-Körne, and M. M. Nöthen, "Genetics of dyslexia: the evolving landscape," J. Med. Genet., vol. 44, 2007, pp. 289–297.

[14] T. R. Miles and E. Miles, Disleksija - Sto godina istraživanja i prakse, Zagreb: Naklada Slap, p. 22, 2004.

[15] Mayo Clinic, "Diseases & Conditions - Dyslexia," mayoclinic.org, 22 July, 2017. Retrived from: www.mayoclinic.org/diseases-conditions/dyslexia/symptoms-causes/syc-20353552, [Accessed 10 September, 2020].

[16] R. Skiada, E. Soroniati, A. Gardeli and D. Zissis, "EasyLexia 2.0: Redesigning our mobile application for children with learning difficulties," Themes in Science & Technology Education, vol. 7, issue 2/3, 2014, pp. 119-135.

[17] Hrvatska udruga za disleksiju, "Disleksija," hud.hr, 2014. Retrived from: hud.hr/uvod/. [Accessed 25 April, 2020].

[18] Croatian Bureau of Statistics, "Basic schools end of 2018/2019 school year and beginning of 2019/2020 school year," dzs.hr, 30 April, 2020. Retrived from: www.dzs.hr/Hrv_Eng/publication/2020/08-01-02_01_2020.htm. [Accessed: 5 September, 2020].

[19] M. Kazakou, S. Soulis, E. Morfidi and T. A. Mikropoulos, "Phonological Awareness Software for Dyslexic Children," Themes in Science & Technology Education, vol. 4, issue 1, pp. 33-51, 2011.

[20] N. Diraä, J. Engelen, P. Ghesquière and K. Neyens, "The Use of ICT to Support Students with Dyslexia," Holzinger A., Miesenberger K. (eds) HCI and Usability for e-Inclusion. USAB 2009, LNCS 5889, 2009, p. 457–462.

[21] E. Staels and W. V. Den Broeck, "Orthographic learning and the role of text-to-speech software in Dutch disabled readers," Journal of Learning Disabilities, vol. 48, issue 1, 2015, pp. 39-50.

[22] D. L. Share, "Phonological recoding and self-teaching: sine qua non of reading acquisition," Cognition, vol. 55, issue 2, 1995, pp. 151–218.

[23] A. Y. Alsobhi, N. Khan and H. Rahanu, "Toward Linking Dyslexia Types and Symptoms to The Available Assistive Technologies," 14th IEEE International Conference on Advanced Learning Technologies - ICALT, Greece, pp. 597-598, July 2014.

[24] A. Y. Alsobhi and K. H. Alyoubi, "Adaptation algorithms for selecting personalised learning experience based on learning style and dyslexia type," Data Technologies and Applications, vol. 53 issue 2, 2019, pp. 189-200.

[25] T. E. Hall, N. Cohen, G. Vue and P. Ganley, "Addressing Learning Disabilities With UDL and Technology: Strategic Reader," Learning Disability Quarterly, vol. 38, issue 2, 2015, pp. 72-83.

[26] S. Mohd Daud and H. Abas, "'Dyslexia Baca' Mobile App –the learning ecosystem for Dyslexic Children," 2nd International Conference on Advanced Computer Science Applications and Technologies, Malaysia, pp. 412-416, December 2013.

[27] V. Zakopoulou, E. I. Toki, G. Dimakopoulos, M. Mastropavlou, E. Drigkopoulou, T. Konstantopoulou and A. Symvonis, "Evaluating new approaches of intervention in reading difficulties in students with dyslexia: the iLearnRW software application," Journal of Education and Practice, vol.8, issue 27, 2007, pp. 36-52.

[28] T. Thomas Cuschieri, R. Khaled, V. E. Farrugia, H. P. Martinez and G. N. Yannakakis, "The iLearnRW Game: Support for Students with Dyslexia in Class and at Home," 6th International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES), Valletta, pp. 1-2, September 2014.

[29] W. G. Alghabban, R. M. Salama and A. H. Altalhi, "Mobile cloud computing: An effective multimodal interface tool for students with dyslexia," Computers in Human Behavior, vol. 75, 2017, pp. 160-166.

[30] L. Rello, Y. Otal and M. Pielot, "A Computer-Based Method to Improve the Spelling of Children with Dyslexia," 16th international ACM SIGACCESS conference on Computers & accessibility - ASSETS' 14, Rochester, NY, pp. 153–160, October 2014.

[31] L. Rello, C. Bayarri and A. Gorri, "What is Wrong with this Word? Dyseggxia: a Game for Children with Dyslexia," 14th international ACM SIGACCESS conference on Computers & accessibility - ASSETS' 12, Boulder, Colorado, pp. 219–220, October 2012.

[32] A. Fernandez-Lopez, M. J. Rodriguez-Fortiz, M. L. Rodriguez-Almendros and M. J. Martinez-Segura, "Mobile Learning Technology Based on iOS Devices to Support Students with Special Education Needs," Computers & Education, vol. 61, 2013, pp. 77-90.

[33] Á. F. López, "A mobile app helps children with special needs improve language and social skills," eurekalert.org, 2012. Retrived from: www.eurekalert.org/pub_releases/2012-12/uog-ama121112.php, [Accessed 12 September, 2020].

[34] V. W. Berninger, W. Nagy, S. Tanimoto, R. Thompson and R. D. Abbottc, "Computer instruction in handwriting, spelling, and composing for students with specific learning disabilities in grades 4–9," Computers & Education, vol. 81, 2015, pp. 154-168.

[35] O. Sitra, V. Katsigiannakis, C. Karagiannidis and S. Mavropoulou, "The effect of badges on the engagement of students with special educational needs: A case study," Education and Information Technologies, vol. 22, 2017, pp. 3037–3046.

[36] M. R. U. Saputra, "LexiPal: Design, Implementation and Evaluation of Gamification on Learning Application for Dyslexia," International Journal of Computer Applications, vol. 131, issue 7, 2015, pp. 37-43.

[37] D. Gooch, A. Vasalou, L. Benton and R. Khaled, "Using Gamification to Motivate Students with Dyslexia," Conference on Human Factors in Computing Systems - CHI 2016, San Jose, California, pp. 969-980, May 2016.

[38] O. Barden, "Facebook levels the playing field: Dyslexic students learning through digital literacies," Research in Learning Technology, vol. 22, 2014, pp. 18535-18553.

[39] Varghese, Sajan; Shahna, E; Neethu Subash; G., "Dyslex_Re: The Real-Time Assistance for Dyslexic People," Global Journal of Computer Science and Technology, vol. 19, issue 2, 2019, pp. 23-29.

[40] A. Kumar and N. Karie, "Development of basic learning and communicationsystem for school children with speech disabilities using mobile platform," International Journal of Advanced Research in Computer Science, vol. 5, issue 6, 2014, pp. 188-191.

[41] Z. Pirani and M. Sasikumar, "Assistive E-Learning System for the Learning Disabled," Procedia Computer Science, vol. 45, 2015, pp. 718-727.

[42] M. &. T. A. Khemaja, "Towards Situation Driven Mobile Tutoring System for Learning Languages and Communication Skills: Application to Users with Specific Needs," Educational Technology & Society, vol. 19, issue 1, 2016, pp. 113–128.

[43] S. Purkayastha, N. Nehete and J. Purkayastha, "Dyscover — An Orton-Gillingham approach inspired multi-sensory learning application for dyslexic children," World Congress on Information and Communication Technologies - WICT 2012, Trivandrum, India, pp. 685-690, October-November 2012.

[44] A. Zorić, "Uporaba informacijsko-komunikacijske tehnologije u radu s učenicima s disleksijom," Edukacijsko-rehabilitacijski fakultet, Sveučilište u Zagrebu, Zagreb, 2019.

[45] A. Meštrović, S. Martinčić-Ipšić and M. Matešić, "Postupak automatskoga slogovanja temeljem načela najvećega pristupa i statistika slogova za hrvatski jezik," Govor, vol.32, br. 1, pp. 3-34, 2015.

[46] A. Šarac, "Use of multimedia in the education of children with dyslexia," University of Zagreb, Faculty of Humanities and Social Sciences, Zagreb, 2019.

[47] I. Habek, "Isprobali smo OmoReader, aplikaciju s kojom je čitanje e-knjiga svima manje zamorno," srednja.hr, 6 January, 2020. Retrived from: www.srednja.hr/svastara/citanje-e-knjiga-odsad-je-jednostavnije-omoreader-donosi-pregrst-lektirnih-naslova-bez-gubljenja-u-redcima-i-malim-fontovima, [Accessed 20 September, 2020].

[48] ICT-AAC, "Learning to Read," www.ict-aac.hr. Retrived from: http://www.ict-aac.hr/index.php/en/developed-applications/android-applications/learning-to-learn, [Accessed 21 September, 2020].