Design and Development of an Android App (HanDex) to Enhance Hand Dexterity in Children with Poor Handwriting

Smitha John¹, Renumol V.G.²

¹School of Engineering, Cochin University of Science and Technology, Kerala, India
²School of Engineering, Cochin University of Science and Technology, Kerala, India

Corresponding author: Smitha John (e-mail: smithajohnkunnel@gmail.com).

ABSTRACT: According to the oscillation theory of handwriting, letters are formed by the coupled modulation of horizontal and vertical oscillation of our hands. This modulation-oscillation scheme requires human motor control. Hence one of the reasons for poor handwriting is lack of fine motor skills. The main objective of this study is to design, develop and evaluate a hand therapeutic-application (HanDex) for children with writing difficulties, to enhance their hand dexterity. Hence this paper describes the design, development and evaluation of the HanDex app. It has mainly five activities for improving tripod grip, hand-eye coordination, spatial organization, letter formation and fine motor skills. The main principle behind the design of all these activities is the oscillation theory of handwriting. A set of user interface (UI) guidelines have been followed in the UI design for simplicity, user-motivation, easy navigation, etc. User evaluation of the prototype was conducted by ten participants in five iterations and the final product was built by considering their feedback. After that, we have conducted case studies in two primary school children with poor handwriting to test the effectiveness of the application. The study used a single subject pretest-posttest design to observe and measure the efficacy of the HanDex application. The post test results showed a positive impact on letter formation, size of letters, spacing of letters and words, placement, speed and legibility in these children. Hence the HanDex app is promising and warrants further investigation on more children with different levels of handwriting difficulty.

INDEX TERMS Digital tools, evolutionary prototyping, fine-motor skill, HCI principles, handwriting difficulty, hand dexterity, Tablet PC, touch-based interfaces.

I. INTRODUCTION
Impaired handwriting is a specific learning disorder. One of the reasons for it is poor motor coordination which leads to poor letter formation and ordering. It is also a brain disorder that may interfere with the spelling, organization of thoughts, and spatial planning and handwriting performance of children [39] [81]. According to Davis Ronald’s book, the occurrence of writing disorders is about 5% to 20% in school children [17]. An average child usually spends his/her 30 to 60 % of the time on handwriting activities in the school [64]. Handwriting is a part of cognitive, kinesthetic, and perceptual-motor functions [21]. Children with writing disorder (Dysgraphia) experience various core handwriting problems such as illegible handwriting, poor motor control, poor spatial planning, inconsistent form and size of letters, speed stroke etc. Poor handwriting may negatively affect self-esteem and academic success of a student [14]. Moreover, legible handwriting is a significant achievement in academic life. Hence it necessitates deeper research studies from educators and health professionals [25].

Recent research in digital technologies realized the effectiveness of contemporary technologies in assisting children with learning and academic disabilities [78] [79]. Increased use of technology in education is obvious with the extensive range of digital applications and smart devices, which can help educators to improve their students' performance inside and outside of the classroom [58]. Researchers are now focusing on special learning environments and developing interactive applications using digital technologies, which can address different disabilities in the early stages [99]. It can be used to train, assist, and stimulate the student’s learning process [99]. Researchers have suggested that the latest education technologies may make the students more creative and improve their learning.
abilities [75]. The transformation from traditional teaching methods to technology-enhanced learning has profound implications for teachers and children with special needs [43][70]. Despite traditional educational systems, emerging technologies with different drives are beneficial for enhancing the teaching-learning process [97]. Different studies have shown that touch devices such as tablets and smartphones help children with writing difficulties to correct their writing through automated exercises and activities [29] [48] [83] [99] [66]. This can foster the academic success of young children [65]. Hence the primary objective of this study was to design and develop a touch-based, therapeutic application to enhance hand dexterity for handwriting readiness.

II. RELATED WORKS
From a set of recent scientific studies [56] [69] [2], it is obvious that digital technologies play an important role in transforming education. Kelly A. Harper, et al., has found that assistive technology may have a positive implication on both academic and non-academic activities for children with learning disabilities [52]. This has positively influenced the learning experience and improved the educational ambitions of young children [56]. Neumann and Neumann [69] say that early experiences with digital technologies are shaping children’s communication and literacy skills. A large amount of research is currently being conducted in exploring the benefits of using ICT as a learning platform for individuals and especially children with learning difficulties [101]. The potential benefits of mobile devices such as laptops, personal digital assistants, and mobile phones have been explored as a learning tool in the classroom and for outside learning [109]. Empirical evidence provides a promising path for research in the design of digital learning environments [34] [62]. Hence the integration of digital technologies in occupational therapy interventions was found to be effective. Belson et al. [7] showed that a digital pen can be used to increase the quality of note-taking strategies and reduce cognitive effort during note-taking. Oyelere et al. [73] have identified that mobile learning applications have a positive impact on student’s learning achievements. Mobile learning systems have a higher penetration rate than laptops, desktops and they offer convenient and cost-effective ways to access higher education [113] [114]. Nedungadi et al. [68] have found that the use of mobile technology and Whatsapp along with other applications can empower teachers and improve the quality of education. Research findings have suggested that conceptualized learning applications can encourage children to master their academic skills [47]. Zhang [117] has explored the benefits of computerized training on students’ writing behaviors and their written products. Innovative technologies enabled the learners to access their education at a lower cost and with a high degree of reliability [2] [81]. It has been identified that use of mobile computing devices leads to an increase in the quality and quantity of learning outcomes [27] [110].

In school-aged children, about 10 to 30% are reported to experience difficulties in mastering handwriting skills [54]. It may have an impact on children’s psycho-social development. Poor handwriting is a neuro-motor condition and it is characterized by faster and cruder movements, lack of inhibition in co-movements, and poor coordination of fine motor skills [96]. Students with writing difficulties lack automaticity in handwriting skills including letter inconsistencies, irregular letter size and shapes, poor spatial organization on the line and page, and unfinished letters [86]. Graham and Miller say that parents and teachers should be aware of the different types of handwriting difficulties and the various learning strategies for their children. The different learning strategies can be tailored as per the needs of the individual. This may decrease children’s frustrations [31]. Enstrom has mentioned that in the school curriculum, handwriting is one of the poorest elements taught by teachers [24]. Hence the children in the school require remediation programs for improving their handwriting. Research on technology reveals that the software tools will not replace good or adequate teaching, but acts as enhanced instruction to meet the student’s individualized learning needs [16]. Moreover, these supporting aids are considered as an element of future development in technologies for the classroom [18].

Researchers have explored the potential benefit of automated analytic techniques in understanding handwriting difficulties [95]. Many researchers [11] [26] [65] [57] have recently shifted their attention to the effectiveness of technology-assisted instruction on the learning-outcome of students with mild and moderate disabilities, especially in the basic skill areas of reading, written expression, language, and mathematics. Therefore, researchers were exploring the benefits of integrating productive applications on tablet computers for elementary school education [18]. One of the studies has assessed the impact of a digital notebook with personalized exercises and extrinsic feedback in beginning writers. The findings from the study showed that the stylus oriented tablet application has a positive benefit in acquisition of handwriting skills in kindergarten children [10]. Similarly, a study on haptic-based application found it to be effective for acquiring handwriting skills in both adults and children [74]. EasyLexia, is a mobile application for children with learning difficulties and the authors claimed that it is a promising tool [101]. Liu has found that integration of multimedia instructions based on the multimedia learning theory was effective for elementary school students in mathematics [57]. Chang and Yu [14] have identified that computer-assisted handwriting practices with sensory feedback can improve writing quality and fluency. Another study has identified that concrete feedback in the form of visual cues played an important role in self-correction [59]. Hamilton has identified that multisensory associative guided instruction can be used for enhancing the spelling ability of dyslexic children [37]. A study on kinder tools using specific activities found that those activities were effective in enhancing the fine motor and visual-motor perceptual skills [61]. Lin et al. [57] have investigated the
effect of tablet computer applications for fine-motor skill development in preschool children. From the study, it has been found that tablet computer applications might be advantageous for educational and therapeutic purposes. Whittaker et al. have identified that a properly designed stylus with touch technologies encourages handwriting development in children with cognitive and fine motor delays [115]. Similarly, Berninger et al. [9] have investigated the effect of iPad based writing instructions for 4-9 grade students with specific learning difficulties. Results from the study showed that computerized writing instruction helped the children to improve their handwriting skills. Hopcan and Tokel (2021) have explored the effectiveness of a mobile writing application for acquisition of handwriting skills in children with dysgraphia. From this study, the authors have found that the students acquired their handwriting skills in terms of letter formation, spelling and words [42]. Kim et al. say that if an intelligent user interface can determine children’s fine motor skills automatically, teachers and parents can assess children’s fine motor skill ability and help children to improve via practicing drawings with touch-enabled devices or pencil and paper [53]. Research explores the use of a tangible environment which provides specific affordance for students in future studies and this will help them to develop their domain knowledge [98].

We have found different applications offering fun and creative ways to practice fine motor skills in early learners. Applications such as Xylophone, Bugs and Buttons 2, Dexteria Jr., iTrace, iWriteWords, Writing Wizard, LetterSchool, Jake’s Never Land Pirate School, Touch and Write Phonics, Tozzle etc. are specifically designed for early learners to encourage their motor skill development [88]. Kids can easily download these applications from app stores and start practicing. But the effectiveness of many of these applications are not substantiated by researchers. The application ‘Xylophone’ is for early learners to encourage fine motor practice in non dominant-hand. ‘Bugs and Buttons 2’ is a game oriented application and may be beneficial for children with dyspraxia and other fine motor issues. ‘Dexteria Jr’ is one of the applications designed for the youngest children with special needs. The application ‘iTrace’ is handwriting skill practice app for young learners to develop letter writing and may be useful for children with fine motor problems. Similarly, ‘iWriteWords’ is a letter practice application for children. The application ‘Writing Wizard’ is for kids to learn cursive handwriting [89]. Learning cursive handwriting is difficult but it increases neural activity of the brain [93]. The application ‘LetterSchool’ is a handwriting stimulating app with animated features and helps the children to remember the correct letter formation. ‘Jake’s Never Land Pirate School’ is one of the applications used for early learners. ‘Touch and Write Phonics’ is a letter tracing app for beginners. The application ‘Tozzle’ is used for developing hand-eye coordination in children. EasySketch is a sketch-based educational application for enhancing fine motor skills in children using sketching and writing activities [53]. Martens et al. have mentioned that most of the educational apps under ‘educational categories’ are not based on established curricula and have not received any inputs from developmental specialists or educators [59]. Another touch-based application named ‘Write-Rite’ claims that it can be used for enhancing handwriting proficiency in children with dysgraphia [85].

From the literature review, it is evident that technological tools have potential to scaffold the student’s special learning needs. This motivated the authors to design and develop a software application to enhance the hand dexterity in children with writing difficulties.

III. SUPPORTING THEORY FOR HanDex APPLICATION

Handwriting difficulties are one of the common issues in children and it is mostly faced by school-aged children. A human handwriting sample can be related to different motor abilities of a person and to the theory of handwriting. Handwriting production is viewed as a constrained modulation of an underlying oscillatory process [41]. Moreover, there are a lot of theories associated with handwriting generation. For example, the Kinematic Theory of rapid movements proposed by R. Plamondon stated that the production of rapid movements by hand is the result of a log-normal impulse response from agonist and antagonist neuromuscular systems [82]. According to Pei et al. letter stroke resembles a well-structured pattern. Also, the pattern function was validated by its significant associations with kinematics of handwriting, style of language, cognitive abilities and hand [77].

The 3 basic components such as sensory, perceptual-motor, and cognitive skills are required in order to accomplish handwriting performance [25]. Hence the fundamental idea was to develop a touch-based application to provide a set of hand therapeutic activities for children with poor handwriting to improve their hand dexterity. It has been decided to develop a prototype of the proposed application with the known software requirements and then gradually evolve to a final product through iterations. The application is named ‘HanDex’ since it is intended to improve hand dexterity. Shamir-Inbal and Blau [99] have recommended that teachers should integrate tablet computers in the instructional design. Moreover these therapeutic activities are intended to improve hand dexterity. Hence all the activities are designed for tablet computers and hence are touch-based activities. These activities are Finger Aerobics (Pinching Activity), Hand-Eye coordination activity (Pattern Trace), Letter pick-up, Art with Geometry, and Letter-Tracking activity.

The pinching activity in the software application was mainly intended to develop tripod grip in fingers to hold a pen/pencil and to improve their hand-eye coordination. In this game-oriented activity the participant has to pinch the ants which are randomly appearing on the screen. There are
different levels in this game and the speed of the activity increases as the level increases. For this purpose, we have used the principle, velocity of the arm movement affects the grip force and this force is used to perform the tasks with the hand [46]. The Hand-Eye coordination activity was developed based on the oscillation theory for handwriting production. This theory postulates that modulations of the vertical and horizontal oscillations are responsible for letter height control and slant constraints [41]. The Letter-Pick-up activities were included in the application based on the alphabetic principle [59]. The fourth activity, Art with Geometry, was designed based on the review of past studies as in drawing the geometrical figures that could improve grapho-motor capabilities, good memory, and early literacy in preschool children [53] [99]. The final activity Letter-Tracing has used the principle of motor learning theory for handwriting improvement [119].

IV. DEVELOPMENT OF PROTOTYPE
This section describes the methodology used for the development of the prototype of the hand dexterity application. We have used the Evolutionary Prototyping Model as our Software Development Life Cycle (SDLC) Model [87] [92], because prototypes can be easily perceived and evaluated by the end-user [1]. Understanding the strength and challenges of a learner can enhance the design of technological tools for education [20]. This is applicable when we develop any software application and understanding the end-user characteristics is beneficial to elicit the requirements. The prototype was developed by going through the phases such as requirement analysis, design, coding, and testing and user evaluation of the prototype. The basic idea was to include some therapeutic activities in the software that may scaffold the children with writing difficulties to enhance their fine motor skills and improve their hand-eye coordination. The prototype of the new software was built based on several HCI guidelines [30] [91]. The following sections describe the various phases of the prototype development.

A. REQUIREMENT ANALYSIS
In this phase, we have visited various special schools and early intervention centers in Kerala, India such as DEIC (District Early Intervention Centers of Alappuzha and Ernakulam in Kerala) and ECHD (Enlight Centre for Holistic Development, Trivandrum, Kerala); for understanding their problems and requirements. We have interacted with different stakeholders such as occupational therapists, doctors, special educators, clinical psychologists, and parents, to know more about the interventions used, specific remedial approaches, the relevance of technology in special education, traditional teaching instructions used for children with writing difficulties, and the demographic characteristics (age, gender, etc.) of the children. The details on these aspects have been collected from these schools and intervention centers. The interaction gave us an insight into the procedures used in each center to identify the children with learning disabilities (LD), their remediation methods, the scarcity of teachers to give personal attention to each child, the long-duration required to train each child, students' interest in electronic gadgets compared to the conventional methods, the characteristics of LD children such as their motor disorders, cognitive impairments, etc. All these aspects point towards the necessity for technology-based training for LD children.

When we interacted with the stakeholders, we specifically asked about the common handwriting difficulty among the children with dysgraphia. They have mentioned different indicators such as cramping of fingers, wrist, and palms while writing, difficulty in letter-formation, poor legibility, poor pencil grip, poor spatial planning on paper, mixing upper-case and lower-case letters, unfinished letters, etc. One of the clinical psychologists mentioned that writing difficulty could not occur alone in children. It is comorbid and may be associated with Dyslexia, ADHD, Dyscalculia, and other motor difficulties.

During our visit, we have also observed some of the training sessions given by the special educators to the students with writing difficulty and noticed that most of the children have poor fine motor skills, which might have affected their handwriting performance. During the interaction, the occupational therapists have expressed their interest in technology-based solutions and they believe that this will assist students to access the tool more easily. Moreover, we could get an opportunity to interact with the parents of the children with learning difficulties. They have mentioned that it would be beneficial if we integrate technology-based instructional approaches, along with the traditional teaching methods for students with writing difficulties. They said that they can train their children at home, if they have such gadgets or technology-based tools. This insight motivated us to develop a training application with hand therapeutic activities to train children with poor handwriting. Based on the inputs received from all the stakeholders, we have decided to introduce training sessions using an existing fine motor development software application. So we have reviewed the existing applications for fine motor coordination and its scientific studies and finalized to use the app called ‘Dexteria’ for children with writing difficulty. Short et al. have identified that ‘Dexteria’ application has a positive impact on fine motor coordination in non-dominant-hand [100]. Similarly, Larsen et al. have identified that ‘Dexteria’ is a well-developed tablet application for motor practice in stroke patients who struggle with loss of dexterity [55]. Similar to Dexteria, there are other applications based on fine-motor tasks which may improve handwriting proficiency.

A pilot study on children with dysgraphia [48] and a couple of case studies on children with poor handwriting [103] were conducted to check the effectiveness of the application as well as to elicit the initial requirements for building the prototype of the new software. Similarly, the Dexteria app has two motor activities and a letter tracing activity, to improve the fine motor skills in children. The
pilot training was done for 9 children at DEIC, Alappuzha to see whether this application is effective for fine motor development [48]. These 9 participants were diagnosed with dysgraphia by the pediatrician. Another set of case studies were also conducted among two children having poor handwriting as mentioned by their teachers [103]. These studies show that improving fine motor skills may improve handwriting skills because they examined the impact of hand therapeutic exercises using touch devices (iPad) on fine motor skill development and handwriting performance. During the training, the therapists and the parents of the participants were allowed to observe their child’s performance. The study was based on pre-test and post-test. We could measure some changes in their handwriting after a set of training sessions. We have also collected feedback from the parents about our training. After the training session, the parents and the therapists have noticed some minor drawbacks in the existing software system, as the system does not provide any feedback during practices, and one of the activities named ‘pinch it’ was tough for the children. This helped us to comprehend the impact of existing software on children with handwriting difficulties and got convinced of the need for technology-based environments for practicing. We have been motivated by the experiment results and the interaction inputs, confirming the possibility to design and develop a software tool to train children with handwriting difficulties. The insight from these studies helped us to design a set of therapeutic activities based on available theories. Thus, we could elicit the primary requirements for a software application as follows:

1. Provide a simple, multi-touch interface.
2. Provide haptic activities with proper and timely feedback.
3. Provide multiple activities to improve their manual dexterity.
4. Apply HCI principles in software design.
5. Include game-oriented activities with a score, levels, etc. to motivate the children.
6. Provide visualization of the progress of each task (for participants, their parents and teachers).

B. DESIGN OF USER INTERFACES AND SOFTWARE ARCHITECTURE

In this phase, based on the above mentioned user requirements, we have made a quick design to develop a prototype of the software for children with writing difficulties. When it comes to designing apps for children there is limited guidance for app designers [59]. We have followed some user interface guidelines in the design process, such as user expectations, error recovery, user feedback, navigation, reduced cognitive load, simplicity, user motivation, etc., [91] [94]. These guidelines were chosen early in the design phase to make the system more user-friendly and effective for the end-users. Literature suggests that ‘understanding cognitive behavior and requirements of the end-user’ is one of the important factors required for designing an application [36] [108]. Tablets have pedagogical potential in developing digital wisdom and the added value of tablet use is in mobile learning in out-of-class settings [99]. Hence we have designed our activities for a touch-based tablet PC and we have followed the five metaphors of mobile learning applications (using a device as a toolbox, creative mind, participation activator, shared mobile desktop, and the connected world) [67] [99] [111]. Generally, educational games have a positive effect on kids’ learning process and learning experience [76]. Also, gamified learning activities have been identified as a promising technique to engage and improve student’s learning behaviors [45]. Employing multi-touch interactive games in education provides a scaffolding tool for improving student’s learning performances [44]. Therefore, we have included game-oriented activities, to encourage the children to be actively involved in the activities to improve their dexterity skills. We have decided to include five distinct hand therapeutic activities, such as Finger Aerobics, Pattern-Trace, Letter Pick-up, Art with Geometry, and Letter-Trace, to improve fine motor skills in children. These activities were designed based on the handwriting theory and different multisensory instructions for handwriting development [63] [84] [90]. We have followed universal design principles from prior research experiments supportive for therapeutic purposes [33]. The universal design principles used in our design are visual design (e.g., icons, visual complexity), interaction styles (e.g., direct manipulation, menus), and use of input devices (e.g., pointing, dragging, and multimodal touch using a stylus) [12] [30] [38] [107].

To design a software interface, it is important to examine the user’s cognitive development in terms of perception, memory, symbolic representation, problem-solving, and language skills [40]. Therefore, the designers must understand the user’s nature of attachment with technological devices and user perception [72]. The main HCI design principles used in the design such as simplicity, learner expectations, navigation rules, user feedback, etc. are explained in the following sections:

**Simplicity:** A fundamental design principle in mobile applications is to include only the necessary information. We should not overload the user with unnecessary information. Hence it has been decided to make the interfaces as simple as possible after considering the age and the cognitive ability of the users. It has been decided to use English as the language in the interfaces and follow the minimalistic design as shown in the layouts (Fig.1 & Fig.2).

**Learner expectations:** Every user will have certain expectations from the application in terms of symbols used and the functionality provided. The various elements designed for the interface should be easily understandable and should follow existing conventions for symbols and terminology. Since the younger generation is familiar with electronic gadgets like smartphones, computers, etc., we have designed our interactive interfaces accordingly.

**Navigation:** Navigation is an important feature to achieve usability. This will aid users to access the required
information and traverse the application. The navigation controls should be consistent in structure and behavior. We have designed the entry interface with a simple menu (Fig. 1), so that the candidates can easily choose their activities. During the exercises, users can go back and forth by clicking the corresponding button provided in the interface. The prototype is designed in such a way that the pattern-tracing actions are reversible and it allows the users to correct their erroneous actions during the training.

**Layout design:** Since mobile devices have a limited screen area, we have divided the available area to organize the items optimally. Since the app is designed for improving hand dexterity, a major portion of the screen is used as a workspace for hand-therapeutic activities. Most of the other buttons are arranged towards the margins on the screen. Hence the users can easily access the required item on the interface. The layouts of the activities are shown in Fig 2.

**Effective feedback:** The system should provide meaningful and informative feedback for every user action. This prototype is designed to offer immediate visual and audio feedback to the children to focus on their goals. So the interface provides error messages, audio alerts, and visual signals when the user commits mistakes during the training. This helps the children to focus on their therapy exercises and correct their errors during the training.

**User data integrity:** To ensure user data integrity, our prototype has employed a firebase data authentication service to store student’s information, game score, time taken to complete a task and login credentials. It is a real-time database used in android applications and synchronized with Google accounts.

**Instructions for novice users:** The main objective of this principle is to guide the new users. Before the commencement of every activity, a new user should get a set of instructions so that he/she can understand how to proceed with the activity. So each activity starts with an instruction page.

**Reduce the cognitive load of the users:** Excessive information-processing required by a user during the interaction can increase their cognitive load. To reduce the cognitive load, we have offered perceiving visual and audio cues to help the children recognize the activities rather than recall them from their working memory. Also, the content used in the interface is legible and avoids visual clutter on the screen.

**User motivation:** The idea behind this principle is that the interface should engage the users and motivate them to achieve their goals. Thus, we have designed game-oriented exercises, with different levels of difficulty and appropriate rewards based on their performance.

Thus the interfaces in the prototype of the system were designed as mentioned above. The design focuses mainly on modules and interfaces. In addition to the design, a high level view of the system is also drawn to show the structural aspects of the system as shown in Fig. 3.
The application has three types of users: Learner, Instructor, and Admin. Each user should register with the system before logging in and must be connected to the internet to access the database. Initially the learner has to register by giving registration details such as name, class, school, parent’s ID etc., which will be stored in the database. The registered learners can directly login to the application and start their activities, by following the instructions. We have given another user access to the instructor who can add students and monitor student’s performance. Instructor has the provision to send emails to the parents. The third user Admin can access the user information and can interact with the system for adding, editing, deleting, troubleshooting, etc.

Firebase auth: This library allows user verification and stores user login credentials.

Text to voice: Text to speech Java library in Java SDK, which provides a high-quality audio stream and allows Java applications to incorporate speech synthesis into the user interfaces.

Pixel manipulation: Here we have used Android Bitmap classes in java to store the image content into memory for user interaction.

C. CODING

The prototype was implemented by using Android development kit SDK version 28, Glide version 4.9.0 for image view, and UNITY 2019.2.9f1 for developing the game-oriented activity. The user interfaces are defined through XML files and XML layout files place a view-instance for the user's response. This system uses a firebase authentication API service to manage the user login and registration. To enable data security, the application uses Firebase authentication libraries Firebase auth 11. +. + and, Firebase real-time database 11. +. +. It stores all the records of the learner including name, class, school, parent’s login credentials as well as their performance data and time for completing each activity. The prototype is developed in such a way that it can store the activities data of each child during the training and allows the parents and teachers to monitor the performance. We have used the following libraries to implement the prototype:

Firebase database: This library has been used to store student performance such as the time of completion, accuracy-based score in tracing activity etc. The score is an indication of how accurately the student could trace the given path and it is a pixel-based calculation which is coded in the programs. This information can be used to generate messages during the activity.

Firebase storage: Used to upload the images produced by the learner to cloud storage. Moreover, a firebase real-time database is a cloud database and the data is imported as well as exported to JSON (JavaScript Object Notation). As mentioned earlier the system has mainly five hand therapeutic activities. The next section describes each activity.

D. HAND THERAPEUTIC ACTIVITIES

The core part of the prototype is a set of hand-therapeutic activities designed to enhance the hand dexterity for better handwriting. Visual-motor integration and hand-eye coordination skills are the two predictors of the quality of handwriting [50]. In other words, visual-motor tasks are functioned by the major part of the brain, so the neurological condition plays an important role in the development of motor skills [105]. Handwriting assessment should take into account general visual-motor abilities, handwriting process and product measures, and tripod pinch strength [21] [80]. This information should be included in designing interventions for handwriting deficiencies [8]. Eye-hand coordination and visual-motor integration are represented by different tasks such as tracing, copying forms, relying upon dots to reproduce a shape (spatial relations), and drawing geometrical shapes [106]. Hence various activities for hand-eye coordination, finger aerobics, etc. are embedded in the application based on the existing studies [31]. This Human-Machine interactive learning environment may help to enhance the user’s fine-motor skill, visual-motor integration, tripod grip, alphabet formation etc. through the tracing, drawing, and pinching activities. The five activities in the application prototype are named as Finger Aerobics, Pattern-Trace, Letter Pick-up, Art with Geometry, and Letter-Trace. These activities have the potential to enhance hand dexterity because they are based on some existing principles. Finger
Aerobics is a game-oriented activity where the child has to pinch on the screen to pick the ants that are randomly appearing on the screen. This would develop the grip force on the forefinger (index finger) and thumb to hold the pen/pencil. This activity uses the principle - velocity of arm movement affects the grip-force [46]. The Pattern Trace Activity is a hand-eye coordination activity, where the child has to trace different patterns given. The principle behind this tracing activity is that the horizontal and vertical oscillation is responsible for the production of slanted lines and spatially separated letters [41]. This could also improve their graph-motor skills. The Letter pick-up activity was introduced to familiarize the sound of each letter and the correct order of the spelling of the displayed animals/fruits on the screen. Several studies found that there is a relationship between phonological awareness, children’s interaction of letter-sound knowledge and their understanding of the alphabetic principle [13] [19] [51] [60]. The activity Art with Geometry mainly focuses on tracing and reproducing various mathematical shapes. This could improve graph motor capabilities, good memory, and early literacy in preschool children. This was selected based on drawing acquisition protocol with selected grapho-motor tasks. Mastering these elements is a prerequisite for mastering legible handwriting [22] [28]. The Letter Trace activity is for alphabet tracing (upper and lower case), to help letter-production, based on different movements such as left, right, top, bottom, and curvy lines. This letter tracing activity is selected for developing visual-motor experience of handwriting letters and it facilitates alphabet recognition and production [49]. The following sections describe each activity in detail:

(a) Finger Aerobics: Researchers have suggested that decremented pinch strength may result in reduced motor control in specific muscles of children with dysgraphia. To develop pencil grip/pincer grasp in children, the application employed a 'pinching' activity to improve the grip force to hold a pencil/pen. This pinching exercise encourages fine motor coordination and hand control. During this activity (see Fig. 4) ants appear on the screen randomly and the user has to pinch them using the thumb and index finger to make it disappear leaving a red mark on the screen. The ‘Pinching’ exercise is composed of six different levels of ant-pinching. During this activity, the student has to pinch 30 ants in 60 seconds. At higher levels of the activity, the ants will be moving faster, so as the level increases the player has to increase the speed of the pinching activity. Children can play and proceed in each level of the game in a user-friendly manner. When they complete one level successfully, the system generates ‘success’ messages at different levels and may motivate the child to involve more in the game. Mainly this activity is aimed at improving the tripod grip and it may also increase the hand muscle strength.

(b) Pattern Trace: This activity helps children to improve their graph-motor skills, by tracing different patterns (sinusoidal, saw-tooth, square wave etc.) (see Fig. 5). To trace different shapes, children have to follow the tracing paths from left to right, top to bottom, through jagged and curved lines within a designated space. They have to draw a pattern by connecting the red points in the pattern. The red points were placed where there is a maximum point of curvature which followed the rule of stroke segmentation based upon the curvature [118]. The oscillation theory of handwriting motivated us to design these patterns so that children can trace these patterns and improve the modulation of horizontal and vertical oscillation of their hands, and this horizontal and vertical oscillation is responsible for the production of slanted lines and spatially separated letters [41]. This can help to enhance fine motor control over letter formation and orient their hand movements in different directions.

In this activity, the students have to make their hand movements according to the trace path. During this time the system generates visual and audio cues such as ‘Going good, continue tracing’ when they go correctly through the tracing path and the system generates messages such as ‘Going wrong, try again’ when students deviate from the tracing path. The system identifies the deviation from the given path by making a pixel-based comparison of the given path and traced path. The system generates the message ‘success’ when a student completes the tracing path as per the instructions. The score of a tracing activity indicates how accurately the participant has traced the path and it is calculated by dividing the total number of pixels in the path by the number of pixels the participant could correctly trace. Its percentage shows the accuracy level with which the child could trace the path. These score calculations are coded as expressions in the programs.

(c) Letter pick-up: This activity (see Figure 6) mainly focuses on the child’s ability to recognize and identify the alphabets connected with particular words using phonemes. Here we have used different libraries of objects (animals and fruits) to represent the word for alphabet recognition. In this activity the child has to recognize the animal/fruit displayed on the screen and pick the correct alphabets for that object from the given jumbled alphabets shown by the system. The principle behind this activity is that ‘learning and practicing
with the sounds of letters make phonics concepts in the brain [63].

(d) Art with Geometry: This activity (see Fig.7) may help children to draw the geometrical figures with the correct shape to encourage curved movements and spatial organization. It includes two subtasks such as drawing a geometric figure and concentric circles. Here children have to trace the circle initially and then they have to reproduce a circle based on the given radius and center point.

This activity may help to develop good control over drawing vertical, horizontal, and round-shaped structures that enhances visual-spatial skills [102]. The principle behind this activity is that drawing different geometric shapes is formative for the development of writing skills and fine motor control [106].

The second task in this activity is to draw concentric circles. The aim of this activity is to develop visual-spatial ordering in children with writing difficulties. This activity instructs the child to draw an innermost circle along the given path and repeat the same on the remaining outer circle paths (see Fig.8). After that, a self-trial with minimal scaffolding will be introduced (see Fig.9). The child can reproduce the concentric circles along the dotted lines. The space between the circles may influence the children to perceive spatial relationships among the circles.
(e) Letter Trace: Research has proved that visual-motor practice with any symbol could lead to an increase in letter recognition and visual-motor coordination [112] [116]. So we have designed a letter tracing activity (Fig. 10) that mainly helps to learn English alphabet formation. It provides a list of letters (uppercase and lowercase) from which the child can pick one and start tracing. It focuses on hand positions within the four parallel lines to help the child to understand each alphabet’s size and shape. It also enables the orthographic coding skills in children to remember the letters or letter formation [32].

As mentioned earlier, these distinct activities are designed based on various theories for improving hand-eye coordination, spatial organization, tripod grip etc. in children with writing difficulties. The system will provide instructions and feedback from time-to-time during the activities, which would help the users to make correct hand movements on the interface. Each of the above-mentioned activities has a mechanism to display various parameters such as success/failure, score and/or time-taken to complete each task during the activity (see Fig. 11). The system also saves the relevant parameters during each therapeutic activity. For example, parameters such as accuracy value of tracing activity, time taken to complete an activity, number of successful attempts, number of failed attempts etc. will be saved in the firebase database for each activity in the student’s account (see Fig. 12). We have included the textual and graphical representation of these data for monitoring the performance in therapeutic tasks (see Fig. 13 &14). This data generated during the training on each activity will be securely uploaded on a database server in that child’s account and the instructor may analyze this data to assess the daily performance of each child during the therapeutic activities. However, the final handwriting assessment of a child is to be done through a pre-test post-test evaluation method as mentioned in section VI.
After the prototype development, we have conducted prototype evaluation to get feedback on design, usability, functional aspects etc. to develop the actual system.

V. EVALUATION OF PROTOTYPE

After developing the prototype, we have conducted evaluation of the prototype by different participants in multiple iterations. The aim of this testing was mainly to get feedback from the users on aesthetics (color, layout, interaction mechanisms etc.) and ergonomics (navigation, metaphors, information dissemination, feedback mechanism, operability, consistent interaction etc.) of the interfaces and secondly to get feedback about the functional aspects. Ardito [5] says that there is no consolidated evaluation methodology available for e-learning applications. So we have decided to conduct a heuristic evaluation of the prototype to get feedback from children. There were 7 children with/without poor handwriting, an occupational therapist, a researcher in educational technology and a software engineer to evaluate the prototype. Their details are given in Table 1. The purpose was to get maximum feedback from each one on each activity, mainly from a usability perspective. However, we had asked the software engineer and the ET researcher to evaluate the functional aspects of the activities also, which means whether the included activities make sense and would contribute towards handwriting performance. We had 3 phases of activities during the evaluation: give instructions and introduction of the app, exploration and feedback.

Initially, three students (Female/7 years, Male/11 years, Male/12 years) from a special learning center, named Enlight Center for Holistic Development in Trivandrum, have participated in the user evaluation. They have writing difficulties which were assessed by the occupational therapist of this center and they were undergoing hand therapy using traditional methods in this center. The participants were allowed to explore all the five hand therapeutic activities on a tablet computer. After that, we have individually interacted with each child to know their experience and feedback on the activities. The feedback was more or less the same. They have mentioned that they felt difficulty at the higher levels of the pinching activity, where they were expected to do more number of pinching. They have also suggested that increasing the thickness of the tracing path of the activities ‘pattern trace’ and ‘letter trace’ would make it less difficult for them. Since the thickness of the tracing path was thin, they could not score better. They were not satisfied with the navigation provided in the pattern tracing activity.

After the students’ evaluation process, we approached the clinical psychologist of the center to interact with the app and give her feedback. She was observing the students during their usability testing. She explored the system herself and made some suggestions about the application such as to increase the number of geometry objects in the ‘art with geometry’ activity and to increase the number of objects in the ‘letter pick-up’ activity. She also suggested increasing the width of tracing paths, so that it would be easier for students.
She commented that the usage of the word ‘kill’ in the Finger Aerobics activity is inhumane. After collecting the feedback, we have incorporated suitable changes, mainly increasing the width of patterns and letters. We have also added a set of fruit names in the ‘Letter pick-up’ activity along with the animal names.

In the second iteration, the participant was one 15 year old boy (10th standard). He told us that his parents and teachers were asking him to improve his handwriting. We have also observed that the student had an uncommon hand orientation, when he was writing on the notebook. He mentioned that in the pattern tracing activity the saw-tooth dotted lines have some issues. Even if we draw exactly over the dotted lines, the system showed error in the traced pattern. Similarly, when he drew through the path of the circle and completed as per the instructions, the system showed an error when he exceeded the starting point. According to him, the circle was correctly traced by him. He mentioned that if we make any marks by mistake in between the red lines without touching the letter path, the system did not provide any feedback about the mistake. He also suggested giving complex words in the letter pick-up activity. After collecting his comments, we have rectified the mistakes in the pattern and letter tracing activities.

After the evaluation process, he decided to practice with the hand therapeutic activities and interacted with the system for almost 25 hours in a span of eight weeks and shared his experience and observations. He told us that the pinching activity helped him to improve his finger grip, which was his major problem during writing. He also added that the handwriting speed has improved significantly after the practice.

In the next round of evaluation, three students (Female/13 years, Female/13 years, and Male/13 years) from different schools in Ernakulam district of Kerala participated. They had legible handwriting. After the evaluation session, they mentioned that the back and forth buttons are not proper in the application. Also, pointed out that there is an unnecessary delay in the beginning of every activity. They mentioned that including cursive letters would be beneficial for older students because cursive letters are mandatory in higher classes in Kerala. Two of them have suggested increasing the size of the letters in the letter tracing activity. After their evaluation we have incorporated the relevant suggestions in the software.

In the next iteration we have asked an ET researcher (Female/45 years) to evaluate the app and give her suggestions. She provided suggestions to improve the navigation and to give a refresh button in the tracing activities so that they can immediately restart tracing if something goes wrong. She has suggested to keep the interfaces consistent in terms of color, layout, button positions etc. The modified interface is shown in Fig. 15.

She has suggested some changes in the activities also. For example, she has suggested providing the basic circle tracing activity with 3 incremental phases: circle with full support (Fig. 15), with partial support (Fig.16) and circle with minimal support (Fig. 17). In the minimal support we are providing only centre and radius. This incremental approach would help students to easily acquire visual-spatial recognition.

In the next iteration we have asked an ET researcher (Female/45 years) to evaluate the app and give her suggestions. She provided suggestions to improve the navigation and to give a refresh button in the tracing activities so that they can immediately restart tracing if something goes wrong. She has suggested to keep the interfaces consistent in terms of color, layout, button positions etc. The modified interface is shown in Fig. 15.

Another suggestion was to remove the ‘letter pick-up’ activity because it may support learning the spelling of the provided words only. This has nothing to do with the handwriting. She suggested to add a ‘lazy eight’ activity where students can trace through an infinity symbol (Fig.18). Lazy eight is a movement-based brain gym learning exercise that can be utilized as an effective tool for enhancement of
writing performance among first grade pupils [71]. This would help in letter formation, which is pivotal in developing handwriting skill. Students can trace the image with their left hand and with their right hand separately for a specified duration. Moreover, we can ask students to do this activity with their left hand and right hand separately and then by comparing the score for each hand we can identify the student’s hand dominance (Left or Right). The hand with the higher score would be dominant. An equation for score calculation is given in the software. It is based on the accuracy and speed with which the student completes the lazy eight activity. Writing with the dominant hand makes handwriting easier.

FIGURE 18. Screenshot of Hand Dominance (Lazy Eight) activity.

In the letter trace activity, the letter choosing menu was vertically oriented with a radio button and the tracing interface was a separate one (Fig.10). This was not user friendly in terms of navigation. So she suggested bringing a palette of letters on the left side of the screen and keeping the letter-tracing area on the right side. Based on her feedback, we have modified the interface (Fig.19). She has suggested adding a set of simple instructions on how to do the activity, before the commencement of every activity (see Fig. 20). These instructions should be available in a click on every interface, which can help the novices to proceed with their activities without confusion.

FIGURE 19. Screenshot of Letter Tracing activity.

FIGURE 20. Screenshot of instructions for novice

In the fifth iteration, the evaluation of the prototype was conducted by a software engineer (Male/45 years). He commented that if we can provide a help video for the novices, it would be easy for them to start with the activities. We did not consider this because we have provided a one-page instruction at the beginning of every activity and this instruction is available whenever required by clicking a button on the right top corner of every screen. He has suggested providing a writing area for the children so that after their practice they can write and see their progress in the app itself. So we have added an activity ‘Write it’, which provides a writing area with minimal tools (Fig. 21). This can also be used to conduct pretest and post test and the handwritten text can be saved in the student’s account.

FIGURE 21. Screenshot of ‘Write it’ activity.

The initial round of software evaluation was done by 7 children with or without handwriting difficulties. From this software evaluation, we have identified that, mainly the students gave responses about the thickness of tracing activities, difficulty level of the pinching activities, feedback about geometric figures and ease of use. The responses were more or less the same. Moreover, these minor participants had no previous experience in interface evaluation and had no adequate knowledge in the technical aspects of the application. Mainly, in usability testing, a software product is evaluated in terms of aesthetics, software design, functionality and user satisfaction [87]. Since the end users are kids below 15 years, we have included two participants from the software industry and education technology field to check the functional aspects of the software. They have expertise in e-learning application development and software design. They have observed that the features such as visual and audio cues and recovering login credentials in the application were not working properly. They provided some insights into adding relevant features and deleting irrelevant
features. Based on their feedback, we have modified the application. Thus the app has been evaluated mainly with respect to usability requirements and based on the evaluation feedback from the participants, the UI design and some of the activities have been modified. The final menu with 6 hand therapeutic activities and a Writing activity (‘write it’) is shown in Fig. 22.

![Screenshot of HanDex main menu](image)

**FIGURE 22. Screenshot of HanDex main menu**

**VI. CASE STUDIES USING HanDex**

After the 5 rounds of usability evaluation the software was ready for experiment. We have done a comparison of our app with another fine-motor skill application Dexteria and the results are shown in Table 2. HanDex has six hand therapeutic activities to facilitate finger grip, hand-eye coordination, spatial organization, letter formation and fine motor skills. So HanDex has more features and feedback facilities than Dexteria. However, it is essential to conduct experiments to check its effectiveness on children with handwriting issues. So we decided to carry out a couple of case studies in children with handwriting difficulties. The basic aim of these case studies was to measure the impact of HanDex on handwriting performance in children with writing difficulties.

|HanDex| Dexteria|
|---|---|
|It is an Android application.||
|The application comprises six hand therapeutic activities to develop finger grip (game oriented), hand-eye coordination and letter formation in children with handwriting difficulties.||
|The different difficulty level of pinching exercises is encouraging and makes a gaming feel to achieve the goals.|The feedback option is not present in the system, when kids make mistakes.|
|The immediate visual and audio feedback present in the application would help the children to track their mistakes during handwriting and correct them.|This is a paid application.|
|The application is free of cost.||
|The application has provided a writing area for children to conduct pretest-posttest handwriting performances.|There is no writing option in this application.|

**TABLE 2**

COMPARISON OF ‘HanDex’ AND ‘Dexteria’

**A. METHOD**

In the case study, we have used a pretest-posttest single subject design to measure the impact of software application. Initially, we conducted a pretest to know the participant's handwriting performance and finger grip. After the pretest, we gave training to the participants using HanDex, where they were allowed to do various hand therapeutic activities in different sessions. One session was almost one hour long. We have given multiple sessions to a child in different weeks. After the software training, we conducted a posttest to evaluate the handwriting performance of the participants. There were 2 handwriting examiners who evaluated the pretest and posttest samples independently. They have used a handwriting performance rubric taken from [35] which has 8 parameters to assess in a scale of 1-5 leading to a maximum of 40 marks. The parameters are letter formation, placement, letter sizing, spacing of letters, legibility, speed, neatness and spacing of words. Ali et al [3] have used the same rubric for evaluating English handwriting on first graders after a fine motor skill intervention. The Rubric used is given in Appendix A. Each parameter is assessed on a 5 point Likert scale. Since it is a subjective process, after the independent evaluation, both the raters discussed their assessment values and came to consensus wherever they had different values.

**B. PARTICIPANTS**

The participants were two primary school children with handwriting difficulties. The children were 9 years old and were studying in third grade in an aided school in Kochi, Kerala. These children have been selected for the study based on a report from their class teachers. Their parents were also concerned about their poor handwriting skills. They were not clinically assessed for any learning disability. The students participated in the experiments with the written consent from their parents.
C. PRE-INTERVENTION
During this phase, a pretest (see Fig. 29 & 31) was conducted to know the student’s current handwriting performance. We have conducted the experiment in a quiet classroom inside the school campus with the permission of the school management. The participants were asked to copy an English passage on an unruled A4 size paper using pencil without eraser. The experimenter did not use the ‘write it’ facility of HanDex for the pretest because the participants were more comfortable to write on a paper. The class teacher and special educator were allowed during the experiment. After the pretest, the experimenter has evaluated the handwriting samples. Before the intervention, the experimenter introduced the hand-therapeutic application ‘HanDex’, installed in a Samsung Galaxy tablet computer. The participants were made aware that HanDex provides six therapeutic activities such as Finger Aerobics, Pattern Trace, Circle Trace-basic, Circle Trace-Advanced, Hand Dominance and Letter Trace.

D. DURING INTERVENTION
After the pretest, the children were asked to do all the 6 activities on a tablet computer one by one. The first activity ‘Finger Aerobics’ (see Fig. 23) is a game oriented activity to develop pencil/pen grip in children. The second activity ‘Pattern Trace’ (see Fig. 24) is used to develop visual-motor integration. The third activity ‘Circle Trace-Basic’ (see Fig. 25) may help the children to enhance curved movements and drawing skills. The fourth activity, Circle Trace-Advanced’ (see Fig. 26) can help children to develop visual-spatial skills. The fifth activity ‘Hand-Dominance’ (see Fig. 27) is used to identify the dominant hand and also to develop hand-eye coordination in children with writing difficulties. Finally, the ‘Letter Trace’ (see Fig. 28) activity is used to teach letter size and shape (both uppercase and lowercase). The teachers, special educator and the experimenter observed the participants while they interacted with the software application. The experimenter allotted sufficient time for every participant to complete all activities in the software application. Initially, each student has spent more than one hour to complete all the activities in the application. After one week, the participants were mastered and completed the handwriting practices within one hour. The experimenter has provided three training sessions in a week to each participant. Each participant got around 20 hours of handwriting training to develop their hand dexterity.
E. POST INTERVENTION

After the intervention, the experimenter has conducted a post-test similar to pretest and evaluation of these samples were done by handwriting examiners. Then both pretest and posttest results were compared to see the impact of HanDex based training on each case.

CASE 1: The first case is a 9 years old boy with poor handwriting. Initially a pretest was conducted where the experimenter asked the boy to copy an English passage about butterflies. The pretest result is shown in Fig. 29, where we can observe that the student has written the letters in different sizes (especially in the first sentence). We can also see that the pressure applied is not uniform which is an indication of poor finger grip during handwriting. It also reduces the speed of handwriting. Besides this pretest sample, we have also assessed his class worksheets and notebooks, and realized that the student had messy handwriting, spelling difficulties, poor spacing of words and letters, lack of awareness of punctuation symbols, and difficulties in forming different letters such as ‘b’, ‘e’, ‘f’, ‘g’, ‘h’, ‘l’, ‘s’ etc. During the study, we have given three software training sessions in a week and the participant has received a total of 18 sessions to develop his hand dexterity. After the training session, the experimenter has conducted a post-test (see Fig. 30) similar to the pretest for evaluating his handwriting progress. The score of the 8 parameters (letter formation, placement, letter sizing, spacing of letters, legibility, speed, neatness and spacing of words) in the pre-test and the post test of participant-1 are assessed by 2 raters independently. Then they discussed their assessment values and came to a consensus and it is given in Table 3. The results show that the HanDex-based training has an impact on the hand dexterity and the handwriting skills in the participant.

### TABLE 3

| Handwriting Parameters | Pretest Score | Posttest Score |
|------------------------|--------------|---------------|
| Letter formation       | 3            | 4             |
| Placement              | 2            | 3             |
| Letter sizing          | 3            | 4             |
| Spacing of letters     | 3            | 4             |
CASE 2: The second case is a 9 years old girl with handwriting difficulties. Her pretest sample is shown in Fig. 31, where she has written an English passage about butterflies. From the pretest performance, we have observed that the participant had difficulties in writing the letters uniformly, uneven spacing between the letters and words, issues in formation of letters (like 'b', 'c', 'f', 'm' etc.) and spelling difficulties. Based on her handwriting difficulties, we have introduced our hand-therapeutic application to the participant. She practiced the six activities on a tablet computer with 3 sessions in a week and received a total of 18 sessions. Then, we conducted a post test (see Fig. 32) similar to a pretest to see her progress in handwriting performance. The 8 parameters related to handwriting are assessed in a similar way as mentioned in case 1. The score of these parameters in the pre-test and the post test of participant-2 is given in Table 4.

![FIGURE 31 Handwriting performance of participant-2 before intervention](image1)

| Legibility | 4 | 4 |
| Speed      | 3 | 4 |
| Neatness   | 5 | 5 |
| Spacing of words | 4 | 4 |
| **Total**  | 27 | 32 |

![FIGURE 32 Handwriting performance of participant-2 after intervention](image2)

**TABLE 4**

| Handwriting Parameters | Pretest Score | Posttest Score |
|------------------------|---------------|----------------|
| Letter formation       | 3             | 4              |
| Placement              | 1             | 2              |
| Letter size            | 2             | 4              |
| Spacing of letters     | 2             | 3              |
| Legibility             | 4             | 5              |
| Speed                  | 4             | 5              |
| Neatness               | 4             | 4              |
| Spacing of words       | 2             | 4              |
| **Total**              | 22            | 31             |

**F. RESULTS**

The results shown in Table 3 and 4 prove that the HanDex-based training has an impact on the hand dexterity parameters such as letter formation, placement, letter size, spatial organization, speed and overall legibility. Thus we could confirm that touch-based hand therapeutic exercises were beneficial for the participants in improving their handwriting. This is obvious from the pretest-posttest samples also (Fig. 29, 30, 31 & 32).

Nowadays, Technology-based education has a positive effect on learning outcomes in school children. A survey from special educators pointed out the importance of technology incorporated in this field [99]. Empirical evidence from different studies demonstrated that assistive technologies
integrated with traditional therapies consistently improved the children with specific learning disabilities [14] [15] [26] [104]. Moreover, the authors have examined the effectiveness of the Dexterity App in children with dysgraphia [48] and in children with poor handwriting [103]. These pilot studies proved that the iPad based fine motor skill development training seemed to be effective for enhancing dexterity performance. During the evaluation of the Dexterity app, parents of the participating children and therapists have mentioned that this app does not provide any feedback and one of the activities named ‘pinch it’ seemed harder for children. Also, Dexterity is a paid application with the iOS operating system, which is not affordable for children from poor socio-economic backgrounds. Therefore, there is a need for a sophisticated yet simple, and cost-free application to support the students with poor handwriting. This motivated us to design and develop a full-fledged app (HanDex) by incorporating six activities, for improving the hand dexterity in children with writing difficulties. We strongly believe that these activities would be effective since they are implemented to support fine-motor skill development and hand-eye coordination. Moreover, it is based on the famous oscillation theory of handwriting. Our initial case studies proved it. Generally, the handwriting skill gets developed at the age of 7-8 years and attains the automaticity at the age of 9 years [4] [25] [102] [112]. Thus, we have designed and developed the software application for children with an age group of 8-12 years. Research has proven that age appears to influence sensory-processing abilities and affect daily performance tasks, such as handwriting [23]. Similarly, a study has proved that tracing had adverse effects on the development of handwriting performance in children and copying is better than tracing to develop handwriting skill [6]. However, the tracing activities provided in HanDex may help students to modulate the vertical and horizontal oscillations of the writing tool to produce better handwriting.

VII. CONCLUSION AND FUTURE RESEARCH

This paper describes the design, development and efficacy evaluation of an application HanDex, for enhancing hand dexterity in children with poor handwriting. It is an Android application using touch-screen technology. We have followed various user interface guidelines to develop this application. The application mainly focuses on developing fine motor skills and visual-motor integration skills to improve hand-dexterity. It comprises mainly six activities to improve hand-eye coordination, to strengthen hand muscles and pencil grip, and to improve visual-spatial organization. The activities provided by the app may help students to modulate the vertical and horizontal oscillations of the writing tool to produce better handwriting. The main advantage of the app is that it provides audible feedback and visual cues when the haptic interactions in the activities go wrong, so that the child can immediately correct his/her movements. Also, our application provides a gaming feel to make the learning process attractive. This may motivate and guide the child, which can have a positive effect on the learning outcome. Various data during the training such as student login details, their finished task, errors, score for each activity, level of performance etc. would be stored in a database. We have conducted 2 case studies to check the effectiveness of the app. Results show that the application ‘HanDex’ has an impact on letter formation, placement, letter size, spatial organization, speed and overall legibility in children with handwriting difficulties. Thus, the touch-based hand-therapeutic activities are beneficial for fine motor skill development in children with writing difficulties. Based on our case studies, we can recommend that fine motor development activities should be included in the curriculum of school children with an intention to improve their handwriting.

In this digital era, the support of technological tools is complementary to existing remediation methods for children with learning difficulties. It supports parents, special educators, and occupational therapists in assisting children with learning difficulties in classroom premises and in-home practices. In future, we need further training sessions with children having poor handwriting to make more observations and strong conclusions on the efficacy of the software application. Based on the results, we may modify our app further to make it robust. This evolutionary process may need several rounds of evaluation and improvisation till we get a full-fledged app. Another future direction can be integrating a machine learning component into this learning environment, so that occupational therapists or doctors can easily make an early detection of the type of deficits in the writing skills of a child.

ACKNOWLEDGMENT

We thank all our participants, special teachers, and the clinical psychologists of the Enlit Center for Holistic Development, Trivandrum, and the District Early Intervention Centers of Alappuzha and Ernakulam for their participation in our study. We thank Athul Krishna for helping us to code the software application. We also express our sincere gratitude to the participants for their liberal support and feedback during the prototype evaluation.

REFERENCES

[1] Abidi, M. H., Al-Ahmari, A. M., El-Tamimi, A. M., Darwish, S., & Ahmad, A. (2016). Development and evaluation of the virtual prototype of the first Saudi Arabian-designed car. Computers, 5(4), 26.

[2] Abbott, C., Brown, D., Evett, L., Standen, P., & Wright, J. (2011). Learning difference and digital technologies: a literature review of research involving children and young people using assistive technologies 2007-2010. In ESRC Seminar Series: Researching Assistive Technologies.

[3] Ali, N., Jalal, S., & Kiazai, A. N. (2021). Improving the English handwriting of First Graders through Fine Motor Skills Interventions. Pakistan Journal of Educational Research, 4(4).

[4] Amundson, S. J., & Weil, M. (1996). Prewriting and handwriting skills. Occupational therapy for children, 3(1), 524-541.

[5] Ardito, C., Costabile, M. F., Marsico, M. D., Lanzilotti, R., Levialdi, S., Roselli, T., & Rossano, V. (2006). An approach to usability evaluation of e-learning applications. Universal access in the information society, 4(3), 270-283.
[6] Askov, E. N., & Greff, K. N. (1975). Handwriting: Copying versus tracing as the most effective type of practice. The Journal of Educational Research, 69(3), 96-98.

[7] Belson, S. I., Hartmann, D., & Sherman, J. (2013). Digital note-taking: The use of electronic pens with students with specific learning disabilities. Journal of Special Education Technology, 28(2), 13-24.

[8] Berninger, V. V., Rutberg, J. E., Abbott, R. D., Garcia, N., Anderson-Youngstrom, M., Brooks, A., & Fulton, C. (2006). Tier 1 and Tier 2 early intervention for handwriting and composing. Journal of School Psychology, 44(1), 3-30.

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

[10] Bonneton-Botté, N., Fleury, S., Girard, N., Le Magadou, M., Cherbonnier, A., Renault, M., ... & Jamet, E. (2020). Can tablet apps support the learning of handwriting? An investigation of learning outcomes in kindergarten classrooms. Computers & Education, 151, 103831.

[11] Bryant, D. P., & Bryant, B. R. (1998). Using assistive technology adaptations to include students with learning disabilities in cooperative learning activities. Journal of Learning Disabilities, 31(1), 41-54.

[12] Burgstahler, S. (2009). Universal Design in Education: Principles and Applications. DO-IT.

[13] Cardoso-Martins, C., Mesquita, T. C. L., & Ehri, L. (2011). Letter names and phonological awareness help children to learn letter-sound relations. Journal of experimental child psychology, 109(1), 25-38.

[14] Chang, S. H., & Yu, N. Y. (2014). The effect of computer-assisted therapeutic practice for children with handwriting deficit: A comparison with the effect of the traditional sensorimotor approach. Research in developmental disabilities, 35(7), 1648-1657.

[15] Coutinho, F., Bosisio, M. E., Brown, E., Rishikof, S., Skaf, E., Zhang, X., ... & Daham-Olief, N. (2017). Effectiveness of iPad apps on visual-motor skills among children with special needs between 4y0m–7y11m. Disability and Rehabilitation: Assistive Technology, 12(4), 402-410.

[16] Connor, C. M., Goldman, S. R., & Fishman, B. (2014). Technologies that support students’ literacy development. In the Handbook of research on educational communications and technology (pp. 591-604). Springer, New York, NY.

[17] Davis, R. D., & Braun, E. M. (2003). The Gift of Learning: Proven New Methods for Correcting ADD, Math & Handwriting Problems. Penguin.

[18] Ditzler, C., Hong, E., & Strudler, N. (2016). How tablets are utilized in the classroom. Journal of Research on Technology in Education, 48(3), 181-193.

[19] Dodd, B., & Carr, A. (2003). Young children’s letter-sound knowledge. J. of Language, Speech, and Hearing Services in Schools.Vol. 34, 128–137.

[20] Druin, A. (2002). The role of children in the design of new technology. Behavior and information technology, 21(1), 1-25.

[21] Engel-Yeger, B., Nagauker-Yavuz, L., & Rosenblum, S. (2009). Handwriting performance, self-reports, and perceived self-efficacy among children with dysgraphia. American Journal of Occupational Therapy, 63(2), 182-192.

[22] Engel-Yeger, B., & Rosenblum, S. (2010). The effects of protracted graphomotor tasks on tripod pinch strength and handwriting performance in children with dysgraphia. Disability and Rehabilitation, 32(21), 1749-1757.

[23] Engel-Yeger, B., Hus, S., & Rosenblum, S. (2012). Age effects on sensory-processing abilities and their impact on handwriting. Canadian Journal of Occupational Therapy, 79(5), 264-274.

[24] Enstrom, E. A. (1964). Research in handwriting. Elementary English, 41(8), 873-876.

[25] Feder, K. P., & Majnemer, A. (2007). Handwriting development, competency, and intervention. Developmental Medicine & Child Neurology, 49(4), 312-317.

[26] Fitzgerald, G. E., & Koury, K. A. (1996). Empirical advances in technology-assisted instruction for students with mild and moderate disabilities. Journal of research on Computing in Education, 28(4), 526-553.

[27] Fons, R. P., Mason, E. J., & Smith, T. A. (1989). CLOPPE-Educational software integration for effective classroom instruction. Journal of Research on Computing in Education, 21(4), 473-482.

[28] Galaz, Z., Mucha, J., Zvončak, V., Mekyška, J., Smekal, Z., Safarová, K., & Faundez-Zanuy, M. (2020). Advanced Parametrization of Graphomotor Difficulties in School-Aged Children. IEEE Access, 8, 112883-112897.

[29] Giordano, D., & Maiorana, F. (2014, June). Addressing dysgraphia with a mobile, web-based software with interactive feedback. In IEEE-EMBS International Conference on Biomedical and Health Informatics (BHI) (pp. 264-268). IEEE.

[30] González-Colleros, J. M., Muñoz-Arteaga, J., & Collazos, C. A. (Eds.). (2017). HCI for Children with Disabilities. Springer.

[31] Graham, S., & Miller, L. (1980). Handwriting research and practice: A unified approach. Focus on Exceptional Children, 13(2).

[32] Guan, C. Q., Liu, Y., Chan, D. H. L., Ye, F., & Perfetti, C. A. (2011). Writing strengthens orthography and alphabetic-coding strengths phonology in learning to read Chinese. Journal of Educational Psychology, 103(3), 509.

[33] Guilliksen, J., Gornansson, B., Boivie, I., Blomkvist, S., Persson, J., & Cajander, Å. (2003). Key principles for user-centered systems design. Behaviour and Information Technology, 22(6), 397-409.

[34] Hall, T. E., Cohen, N., Vue, G., & Ganley, P. (2015). Addressing learning disabilities with UDL and Technology: Strategic reader. Learning Disability Quarterly, 38(2), 72-83.

[35] Handwriting Rubrics, Retrieved from https://www.yourtherapysource.com/blog/2015/03/17/free-handwriting-rubric/.
McHale, K., & Cermak, S. A. (1992). Fine motor activities in school children: Preliminary findings and provisional implications for children with fine motor problems. American Journal of Occupational Therapy, 46(10), 898-903.

Mabbett, K. L. (2018). Kinder Tools: the effectiveness of a 12-week intervention program on upper limb disability, manual dexterity, pinch strength, range of finger motion, performance in activities of daily living, functional independency, and general self-efficacy in hand osteoarthritis: A randomized clinical trial. Journal of Hand Therapy, 30(3), 262-273.

Prunt, M., & Barnett, A. L. (2017). Understanding handwriting difficulties: A comparison of children with and without motor impairment. Cognitive neuropsychology, 34(3-4), 205-218.

Plumondon, R. (1995). A cinematic theory of rapid human movements: Part I. Movement representation and generation. Biological cybernetics, 72(4), 295-307.

Plimmer, B., Reid, P., Blagoev, R., Crossan, A., & Brewster, S. (2011). Signing on the tactile line: A multimodal system for teaching handwriting to blind children. ACM Transactions on Computer-Human Interaction (TOCHI), 18(3), 1-29.

Ranganathan, V. K., Siemionow, V., Sahgal, V., Liu, J. Z., & Yue, G. (2012). EasySketch: A Sketch-based Educational Interface to Support Children’s Self-regulation and School Readiness. In The Impact of Pen and Touch Technology on Education (pp. 35-46). Springer.

Rahim, N., & Jamaludin, Z. (2019). Write-Rite: enhancing handwriting awareness, and the phonetization of writing. European Journal of Special Needs Education, 26(3), 283-298.

Rapin, I. (1996). Does easy do it? Children, games, and learning. Game Developer, 5(6), 88.

Pressman, R. S. (2005). Game Developer, 5(6), 88.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/
learning performance: A meta-analysis and research synthesis. Computers & Education, 94, 252-275.

[110] Swan, K., Hoot, M. V. T., Kratcoski, A., & Unger, D. (2005). Uses and effects of mobile computing devices in K-8 classrooms. Journal of Research on Technology in Education, 38(1), 99-112.

[111] So, Y. (2017). Designing for mobile apps: Overall principles, common patterns, and interface guidelines.

[112] Tseng, M. H., & Chow, S. M. (2000). Perceptual-motor function of school-age children with slow handwriting speed. The American Journal of Occupational Therapy, 54(1), 83-88.

[113] Ulrich, C., Shen, R., Tong, R., & Tan, X. (2010). A mobile live video learning system for large-scale learning—system design and evaluation. IEEE Transactions on Learning Technologies, 3(1), 6-17.

[114] Vavoula, G., Pachler, N., & Kukulska-Hulme, A. (2009). Researching mobile learning: frameworks, tools, and research designs. Peter Lang.

[115] Whittaker, S., Rose, N., & Ward, T. (2019). Stylus For Fine-Motor Development. Technical Report.

[116] Zemlock, D., Vinci-Booher, S., & James, K. H. (2018). Visual-motor symbol production facilitates letter recognition in young children. Reading and Writing, 31(6), 1255-1271.

[117] Zhang, Y. (2000). Technology and the writing skills of students with learning disabilities. Journal of Research on Computing in Education, 32(4), 467-478.

[118] Zheng, W., Liu, Z., & Sun, Z. (2006). Curvature-Based Segmentation for Sketch Understanding. In TPGC (pp. 157-164).

[119] Zwicker, J. G., & Harris, S. R. (2009). A reflection on motor learning theory in pediatric occupational therapy practice. Canadian Journal of Occupational Therapy, 76(1), 29-37.

SMITHA JOHN is a Research Scholar at Cochin University of Science and Technology (CUSAT), Kerala, India. She has earned her undergraduate degree from Mahatma Gandhi University, India and master’s degree from IGNOU, Delhi, India. She has worked as Assistant Professor in CUSAT for 7 years. Her research area is Learning Disability and Technological Interventions.

RENUMOL V.G is a Professor in Information Technology at CUSAT, India. She has earned her undergraduate and postgraduate degrees (B.Tech. in Computer Engineering & M.Tech. in Software Engineering) from CUSAT. She has received her Ph.D. in Computing Education from Indian Institute of Technology (IIT), Madras, India. She has received a Postdoctoral Fellowship (PDF) in Educational Technology from Indian Institute of Technology, Mumbai, India. Her research area includes Computing Education, Cognitive Psychology, Educational Technology and ICT in Special Education. She has several publications in these areas.
### Appendix A

| Overall  | 5 | 4 | 3 | 2 | 1 | SCORE |
|----------|---|---|---|---|---|-------|
| Handwriting | All of the letters are formed correctly (more than 75%) | Most of the letters are formed correctly (50-75%) | Some of the letters are formed correctly | Few of the letters are formed correctly | Less than 25% of the letters are formed correctly |
| Placement | All letters are oriented correctly on the lines (more than 75%) | Most of the writing sample is oriented correctly on the lines (50-75%) | Some of the writing sample is oriented correctly on the lines | Little of the writing sample is oriented correctly on the lines | Less than 25% of the writing sample is oriented correctly on the lines |
| Letter Sizing | All letters are sized correctly | Most of the letters are sized correctly (more than 75%) | Some of the letters are sized correctly (50-75%) | Few of the letters are sized correctly (25-50%) | Less than 25% of the letters are sized correctly |
| Spacing of Letters | All letters are spaced correctly (more than 75%) | Most of the letters are spaced correctly (50-75%) | Some of the letters are spaced correctly (25-50%) | Few of the letters are spaced correctly (25-50%) | Less than 25% of the letters are spaced correctly |
| Legibility | All letters in the writing sample are legible (more than 75%) | Most of the writing sample is legible (50-75%) | Some of the writing sample is legible (25-50%) | Little of the writing sample is legible | Less than 25% of the writing sample is legible |
| Speed | Keeps up with peers when completing handwritten assignments | Takes 25% longer than peers to complete handwritten assignment | Takes 50% longer than peers to complete handwritten assignment | Takes 75% longer than peers to complete handwritten assignment | Takes more than 75% longer than peers to complete handwritten assignment |
| Neatness | Writing assignments are always neat without erasures, torn paper or cross outs | Most (>75%) of the writing assignment is neat without erasures, torn paper or cross outs | Some (50-75%) of the writing assignment is neat without erasures, torn paper or cross outs | Little (25-50%) of the writing assignment is neat without erasures, torn paper or cross outs | Less than 25% of the writing assignment is neat without erasures, torn paper or cross outs |
| Spacing of Words | All words are spaced correctly | Most (>75%) of the words are spaced correctly | Some (50-75%) of the words are spaced correctly | Little (25-50%) of the words are spaced correctly | Less than 25% of the words are spaced correctly |

**TOTAL SCORE OUT OF 40:**

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/