Can Students With Dyslexia Learn Independently? A Seven-Week Study of Chinese Character Learning in an Informal Learning Environment

Ka-Yan Fung, Simon Tangi Perrault, Lik-Hang Lee, Kwong-Chiu Fung, and Shenghui Song, *Senior Member, IEEE*

***Abstract*—Dyslexia is a specific learning difficulty that affects primary school students, which is difficult to tackle through traditional school learning due to limited resources. To this end, large-scale digital learning presents new opportunities to address the need for inclusive education. A unique challenge for students with dyslexia in Hong Kong is learning Chinese characters. In this article, we investigate whether students with dyslexia can learn the writing of Chinese characters independently in an informal learning environment. For that purpose, we developed a mobile application for learning to write Chinese characters with three different writing conditions. First, students learn new Chinese characters in *Condition 1: Grid+Contour+Instruction*. Then, students strengthen their memory of the learned Chinese characters in *Condition 2: Grid+Contour*. Finally, students retrieve the memory of the learned Chinese characters in *Condition 3: Grid Only*. Students with dyslexia demonstrated a significant improvement after practicing with the three-condition design. For example, they wrote much slower than students without dyslexia before the study but caught up over time. This study contributes an approach to facilitate the self-paced learning of students with dyslexia at scale.**

***Index Terms*—Assistive learning, coronavirus (COVID-19), digital game-based learning, flexible learning, inclusive education, self-paced learning.**

I. Introduction

Dyslexia is a specific learning difficulty [1], [2], [3], [4] that is estimated to affect 5%–10% of the world population [5], and manifests itself as difficulties in reading, spelling, and writing. In addition, dyslexia also affects the speed of processing information, short-term memory, visual perception, and motor skills [6]. Existing research on dyslexia focused on languages using the Latin script or alphabet [7]. Unfortunately, such results cannot be applied to the learning of Chinese by students with dyslexia because Chinese, e.g., Cantonese, utilizes a logographic writing system where individual characters represent words. Conventionally, students in Hong Kong learn Chinese handwriting in schools, where teachers teach students using a blackboard with chalk or paper cards, and students learn to write by practicing (copying) the learned Chinese characters [8], [9], [10], [11], [12], [13], [14]. However, students with dyslexia do not like repeated and monotonous tasks that students without dyslexia need to go through. One exam of such practices is shown in Fig. 1.

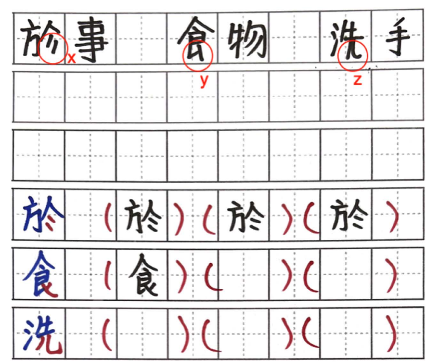

Fig. 1. When students write a character in the wrong way, the teacher highlights the wrong parts, as circled and labeled by x, y, and z in red. Then, the teacher will provide the correct writing and highlight the wrong parts with different colors (the blue and violet in the first block of the last three lines). Students need to copy the character three times within three brackets.

It is widely acknowledged that large-scale digital learning presents new opportunities to address the need for inclusive education [15]. Unlike face-to-face learning, online teaching does not have constraints on location, time, and human resources (e.g., classroom configuration, learning schedule, and qualified teaching staff). Extensive research efforts have been devoted to exploring how online teaching can help develop more inclusive pedagogy and how digital learning can be personalized and adapted to the needs of individual learners [16], [17], [18].

Many researchers have considered massive open online courses (MOOCs) for massive online and informal learning. For example, Papathoma et al. [16] proposed to improve the accessibility of MOOCs in supporting learning around the world. Hudgins et al. [17] focused on MOOC-based online

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Ka-Yan Fung, Kwong-Chiu Fung, and Shenghui Song are with the Hong Kong University of Science and Technology, HKSAR, Hong Kong (e-mail: kyfungag@connect.ust.hk; kcfungag@connect.ust.hk; eeshsong@ust.hk).

Simon Tangi Perrault is with the Singapore University of Technology and Design, Singapore 487372 (e-mail: simon_perrault@sutd.edu.sg).

Lik-Hang Lee is with the Hong Kong Polytechnic University Hong Kong, SAR 00000, Hong Kong (e-mail: likhang.lee@kaist.ac.kr).

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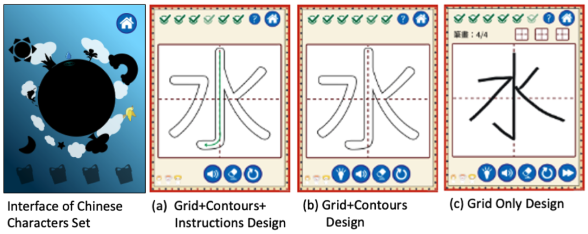


Fig. 2. Three learning conditions used in our study. (a) Learning condition with grid, character contours, and instructions for the stroke. The green line with an arrow represents the instruction for a given stroke. (b) Learning condition with grid and character contours. (c) Learning condition with grid only. A participant drew the character on this image (水, lit. water).

degree programs and tools to create massive informal learning communities [19]. However, most MOCCs are designed for general public education purposes, where inclusive education is usually ignored [20].

Computing-aided learning can enhance students' learning experience by supporting self-regulated learning [18]. However, the related investigation for special education is in its infancy. Some researchers adapted mobile learning technology to support students with special learning difficulties by using puzzles, images, or animated pictograms [21]. Character Alive [22] allowed students to watch the animation to learn how to write a character. Then, students can copy the characters on a handwritten card with grooves. With multichannel information exposure, this tool could help at-risk students with dyslexia retrieve their memory. However, students need to check the correctness of their works by watching some animations and may need help distinguishing between right and wrong. Furthermore, some researchers pointed out that many prior studies used the "one-size-fits-all" approach to develop the learning materials, which is more problematic for students with dyslexia [23], [24]. As a result, the effectiveness of computing-aided learning needs an in-depth investigation, and more inclusive pedagogy needs to be developed.

In this article, we aim to:

1) investigate the learning conditions that can help students with dyslexia learn to write Chinese characters through informal learning, including *Condition 1: Grid+Contours+Instructions, Condition 2: Grid+Contours, and Condition 3: Grid Only,* as shown in Fig. 2,
2) reveal how informal learning can help tackle students' writing problems, and
3) determine whether students' writing speed can be improved by informal learning.

In order to answer the aforementioned research questions, we designed an application for students with dyslexia. Fig. 7 presents the framework of our study, which focuses on learning to write Chinese characters. In stage one of the three learning conditions, *Grid+Contours+Instructions* provides students with instructions on Chinese character writing stroke-by-stroke. Then, the application guides students on Chinese character writing in stage two, *Grid+Contours*. The last stage, *Grid Only*, allows students to practice Chinese character writing at their own pace.

As shown in Fig. 5, the proposed learning framework has two dimensions, i.e., the Chinese learning process and the development of Chinese literacy. In this study, we systematically analyze the process of learning traditional Chinese, including

1) word recognition,
2) character pronunciation,
3) stroke order, and
4) write characters,

which assists students in learning to write Chinese characters progressively [25].

Over the seven-week study period, we collected a total of 2567 data samples from handwriting images: 641 for the *Grid+Contours+Instructions* stage, 590 for the *Grid+Contours* stage, and 1336 for the *Grid Only* stage from 20 effective respondents (i.e., primary schoolchildren studying Grades 1 and 2). In order to keep track of the common writing mistakes. We defined five labels to keep track of students' writing performance. Students with dyslexia improved in three out of the five writing mistakes, namely *standard writing, visual contour integration abilities*, and *proportions of components*. Meanwhile, students without dyslexia made progress in four out of the five writing mistakes, namely *drawing instead of writing, standard writing, visual contour integration abilities* and *missing/added strokes*. The major observations of this study include the following.

1) The three learning conditions can effectively help students with dyslexia learn to write in an informal learning environment.
2) Students with dyslexia improve in three aspects, including *Standardized Writing, Visual Contour Integration Abilities, and Proportions of Components*.
3) Students with dyslexia can write faster after seven weeks of informal learning.
4) Students with dyslexia are more motivated to learn with apps than with paper-based tests.

The rest of this article is organized as follows. Section II introduces the related works, and Section III describes the proposed framework and study design. Section IV explains the experiment in detail, including writing types, participants and procedures, and evaluation metrics. The major findings are reported in Section V, and Section VI discusses the effectiveness of our study. Finally, Section VII concludes this article.

II. Related Works

A. Chinese Languages

In contrast to alphabetical languages, such as English, which values grapheme–phoneme correspondence [26], the correspondence between orthography and phonology is essential for Chinese [27]. In alphabetic orthography, learners can predict the spelling of a character through its pronunciation since there is a connection between letters and their sounds [28]. For Chinese, pronunciation can be a minor key when people need to write down the characters [29]. Instead, remembering a character's specific radicals and components is the only way to write accurately. Also, the educational community emphasizes stroke order throughout the educational process, such as writing horizontal strokes before vertical ones, which increases the difficulty of

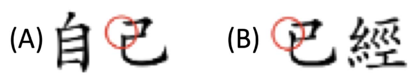


Fig. 3. (A) "自己" (lit. self). (B) "已經" (lit. already). The difference between the two characters is the length of the upper part of the character, indicated by the red circle.

writing Chinese characters. Furthermore, Chinese characters follow strict rules on the building blocks, and slight changes in composition, proportion, and orientation can lead to different meanings and pronunciations. As such, precise visual discrimination of the slight differences in the composition of strokes is needed [30], such as the difference between "已" and "己" (see Fig. 3). On top of this, different compositions, proportions, and orientations of the components can form different characters and, thus, different meanings. The stroke of the dot, "丶" is one of the most complicated strokes since its position can produce different meanings, e.g., "犬" (dog) and "太" (significantly). Similar cases include "叻" (excellent in Cantonese) and "加" (to add). In terms of pronunciation, although the compound characters usually carry a phonetic radical on the right side, these phonological cues are not always reliable. For example, the Cantonese pronunciation of "槍" (gun) is "coeng1," but its phonetic radical is "倉" (warehouse), with the pronunciation "cong1," which is similar to "coeng1." On the other hand, many characters have same or similar sounds. However, they do not have too much meaning in common. For example, "影" (shadow) and "形" (shape) are pronounced as "ying2" and "ying4," respectively, with slight differences in tones but different meanings. Overall, phonological cues may not assist students' memory retrieval in character writing.

B. Difficulties in Learning to Write Chinese in Hong Kong

Handwriting is essential for children throughout their education journey. Students must complete writing tasks, such as dictation, copying, composition, and listening, in school. Daily, they must adequately write their personal information, such as name and home address. It is estimated that primary school students spend over 50% of their time completing tasks related to handwriting [30]. Feder and Majnemer [31] pointed out that students' academic performance and self-esteem are diminished because of the deficiency in handwriting.

Traditional Chinese characters include six types, the so-called Chinese character classification (六書), with 11 structures under the six types, as shown in Fig. 4. It is difficult for beginners to write Chinese appropriately because they cannot master the structure of Chinese characters. It is no surprise that handwriting problems are more common among children learning Chinese in Hong Kong than those learning other alphabetic languages.

In addition to Chinese character classification, Hong Kong students must adapt to the transition from spoken to written Chinese in everyday life. Unfortunately, the lexical and syntactic representations of the spoken language differ from those of the written language [32]. For instance, in spoken Cantonese, the characters for "mobile phone" are "手機" (colloquial), but students need to write "手提電話" (formal). Such situations lead to confusion, whereas the education system does not systematically enhance students' phonological skills for recognizing the characters.

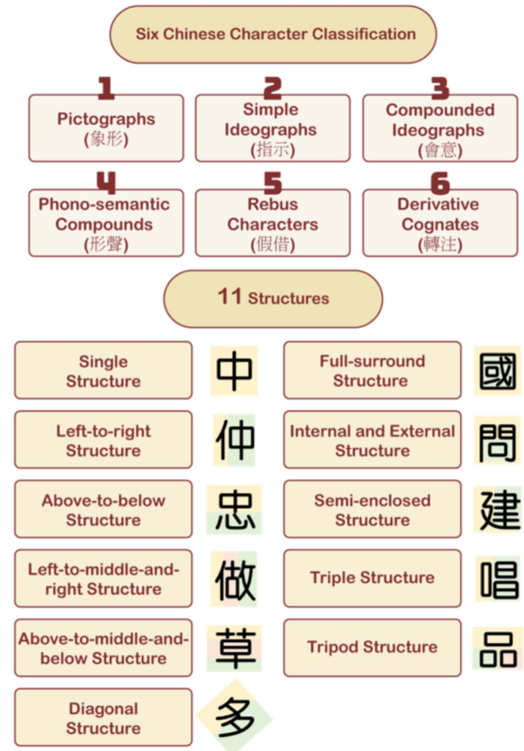


Fig. 4. Upper image shows six categories of Chinese characters, whereas the lower image is the description of the 11 Chinese character structures.

C. Computing-Aided Learning

1) Metaverse and AR in Learning: Metaverse and AR technologies have been widely used in language learning [33], providing opportunities for immersive learning [34]. However, some research found that even experienced teachers tend to focus on the instructional content rather than how AR can help students learn [35]. Also, there is no evidence that younger teachers are more likely than senior teachers to embrace new technologies [36]. The main obstacles are the technology literacy of the teachers and students [35], the availability of infrastructure [37], and the affordability of high-priced devices for underprivileged students.

2) Applications for Dyslexia Training: Traditionally, dyslexia training and early intervention are conducted in clinics with pens and paper. Fortunately, mobile devices make it easier to intervene in dyslexia training. Moreover, digital tools have become more popular and cover the interventions of different dyslexic characteristics, such as spelling problems, handwriting, and memory. Most existing digital dyslexia training tools focus on Latin (or Tamil) alphabets [38], [39], [40]. *DysEggxia* [41] and *Jollymate* [42] provided intervention on spelling skills. *Dleksia Game* [41] provided intervention in the broader areas, including the phonological core deficit, working memory, and auditory deficit.

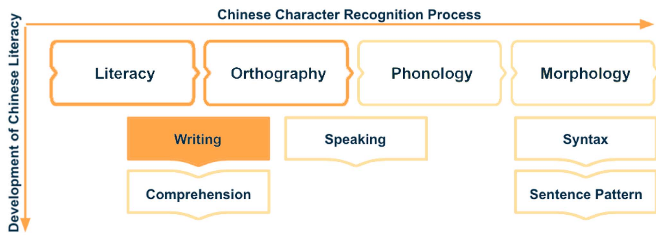


Fig. 5. Framework of learning Chinese. We focus on the stage of writing a character, including literacy, orthography, and writing.

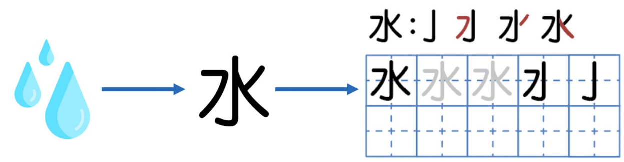


Fig. 6. Pictorial description of a Chinese character is displayed (left). Students have to identify the picture from the Chinese character 水 (lit. water) (middle). Then, students learn how to write the Chinese character step-by-step (right).

3) Applications for Learning Chinese Characters: Chinese Handwriting Speed Test (*CHAST*), the Chinese Handwriting Speed Test, is a tool from Taiwan. The authors of *CHAST* [43] examined the variations between children with slow and regular handwriting speed and the relationship between the factors in perceptual-motor measures and sustained attention. It was shown that handwriting speed is strongly correlated with age for both slow and regular writing groups. *The Visual Training Tool* is an assistive tool from Japan that assists in recognizing and understanding *Kanji* [44]. Students are required to reconstruct the component as a *Kanji*. This tool can help improve students' recognition ability. Nevertheless, there are many differences between *Kanji* and Chinese characters. For example, both "発表" in *Kanji* and "發表" in Chinese, mean "issue," but their components and strokes are different. Also, this tool does not provide a stroke-based learning approach. Another tool called *Chinese Handwriting Analysis System (CHAS)* [45] was designed to analyze students' handwriting performance and assist therapists in identifying primary school students with handwriting problems. Students are required to use a digital writing board (WACOM Intuos 3 digitizer) to finish the dyslexia test, which may not be suitable for students to learn independently.

III. Application Design

A. Proposed Framework

The proposed framework is shown in Fig. 5, which systematically describes the learning process of traditional Chinese. On the one hand, the figure depicts a four-stage journey of learning Chinese, including literacy, orthography, phonology, and morphology, depicted in the horizontal axis. On the other hand, it also includes the three main stages to establish Chinese literacy: writing and comprehension, speaking, and syntax and sentence pattern. We focus on writing in this research. According to the guidelines on Chinese curriculum provided by the Education Bureau (EDB) of Hong Kong [46], schools should focus on cultivating primary school students' (i.e., from Grade 1 to Grade 2) listening and speaking skills. In addition, teachers should cultivate students' interest in literacy and encourage them to know more Chinese characters.

In the Chinese learning process, visual skills are essential to building up the ability of character recognition in the early stage [47]. In contrast, literacy development is highly dependent on orthographic skills [48] and is associated more with later-stage Chinese character recognition [49], i.e., students can differentiate the vocabulary of "winter" as "冬天," instead of "東天." "冬" (winter) and "東" (the East) share the same pronunciation, "dung1."

Furthermore, strong knowledge of phonology can help students retrieve the pronunciation and meaning of Chinese characters [50], and morphological awareness helps children identify the meaning [51] and pick up new characters [52]. Therefore, Chinese character recognition is crucial for students to learn vocabulary.

In developing Chinese literacy, orthographic and morphological awareness are crucial in linking Chinese writing and comprehension. Also, orthographic and morphological awareness are equally important in linking writing with reading comprehension in Chinese [51]. Furthermore, morphology is central at the interface of phonology, syntax, and semantics [53]. Morphological awareness depends on the ability of language users to understand and accurately deploy complex morphological forms [54]. This study focuses on the writing element of the Chinese learning process, which is highlighted in orange in Fig. 5.

In primary schools, students spend nearly half their time in writing [43], such as copying and dictation. Writing clearly and efficiently is vital for formal and informal written communication [78]. Nevertheless, students must write with correct and orderly strokes and neat fonts. If students fail to learn and memorize the rules and principles, writing Chinese characters becomes a problematic task [56]. In practice, students first differentiate pictographs from Chinese characters, as shown in Fig. 6. Understanding the historical origins of ancient Chinese characters is an effective way to learn Chinese characters [57]. Second, students learn the Chinese characters by listening to the pronunciation [58], where they listen to the text recitation every day to prepare for higher level learning after becoming familiar with the single characters. Students can try associating the characters with the pronunciation and pictographs in their memory. Third, students learn the correct stroke order of Chinese characters. When students understand and write the stroke in the correct order, they can master the operation of the strokes and the combination of the structure, and then write the characters neatly [59]. Finally, students write characters step-by-step. Therefore, students should go through recognizing, learning, and writing to build a solid foundation in Chinese character writing [56]. Typical handwriting difficulties include slurred handwriting, inability to keep up with written class assignments, and lack of handwriting automatism [60].

Chinese character recognition (orthography) is the first step to improving students' literacy level (see Fig. 5, Block 1:

Literacy) [61]. It provides a solid foundation for vocabulary and speech processing and plays an essential role in learning the mapping between written and spoken language [62]. A good correlation between character recognition and phonology facilitates learning to read, where character recognition and phonological knowledge mutually help each other [63]. Therefore, phonology enhances students' character recognition development.

Character pronunciation (phonology) is the second step in building students' literacy [64]. Handwriting can help connect characters with their pronunciation [65]. Teachers will read the characters with students to facilitate their memory during class. Students first master the pronunciation of compound characters according to grapheme–phoneme correspondence and then perform legible handwriting [66].

Stroke order training (Writing) is the third step in developing students' literacy [67]. Without the help of digital tools, teachers can only visually check whether students' handwriting is correct through hands-on practice. However, teachers cannot evaluate the stroke order from the students' static marks. As a result, students often write certain Chinese characters in the wrong stroke order, which leads to stroke errors, including stroke addition, stroke deletion, and broken strokes [68]. Therefore, stroke order in Chinese character processing has been established as a motion schema, stored as part of the representation of Chinese characters in memory, and an effective aid in retrieving Chinese character-related information from memory [69], [70].

Writing character (writing) is the fourth step in boosting student's literacy level [71]. Some studies [72] have found that when students receive explicit and supplemental instructions on how to form and fluently write characters, they can improve their handwriting and composition skills. With instructions, students can focus on other essential aspects of writing, such as choosing characters and constructing sentences [73]. As a result, handwriting instruction is critical in overcoming handwriting difficulties, at least for children who struggle to master handwriting skills.

Based on the abovementioned understanding, we developed a mobile application to help students with dyslexia learn Chinese independently. The developed application has several unique advantages. First, the pedagogy design meets users' needs. In particular, it not only focuses on the technology side but also pays attention to the instructional content. Second, the user interface (UI) and game logic were designed following the design-thinking philosophy. Specifically, the UI design is close to the copybook students use in the classroom to reduce uncertainty bias when learning with the new platform. When students write the Chinese characters in the wrong stroke order or out of the grid, the application can automatically detect them and notify the students. We gather all the interaction information and notify the school teacher to pay attention to the student's handwriting problems. Third, the analysis metrics are unique and developed by professionals [74].

B. Study Design

We conducted the study in a local primary school classroom and evaluated the participants' learning efficiency. Students used a mobile application to learn traditional Chinese after school without the teacher's guidance and supervision from September 2020 to December 2020 (seven weeks). Although various learning applications are available, they do not fit our research goals. Thus, we designed our application by comprehensively cover the learning of Chinese character writing in sequential stages, including:

1) *Grid+Contours+Instructions*,
2) *Grid+Contours*, and
3) *Grid Only*.

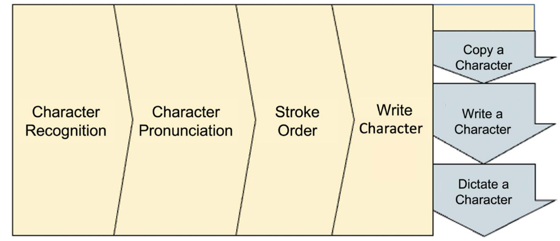


Fig. 7. Our proposed study framework systematically analyzes the process of writing traditional Chinese. The horizontal axis depicts the four-stage journey of learning to write Chinese characters. The vertical axis describes three main stages of writing a character. It is important to note that this is the typical process of learning to write a Chinese character in Hong Kong.

Fig. 7 presents the framework of our study that emphasizes learning how to write a Chinese character. The framework is defined horizontally with the following four steps, namely:

1) word recognition,
2) character pronunciation,
3) stroke order, and
4) write characters,

which assist students in learning Chinese character writing progressively [25]. For example, in the *Write Characters* stage, students would learn how to write a character by following the learning process, i.e.,

1) copy a character,
2) write a character partially, and
3) write a whole character.

C. Handwriting Learning Process

According to the framework shown in Fig. 7, we designed six types of games that encourage students to engage in writing, as shown in Fig. 8. In this study, we only measure the effectiveness of writing, which is related to the games of *Stroke Order* and *Write Characters*.

A new set of Chinese characters is released when the game starts, as shown by the "interface example" at the top right corner of Fig. 8. Students can choose which Chinese characters to write first. After finishing one Chinese character, the corresponding image of the Chinese character changes from black to colorful, as shown by the "interface example" at the bottom-right corner of Fig. 8. The six types of games address the learning framework in Fig. 7, namely Character *Recognition and Character Pronunciation* (A–C on the right-hand side of Fig. 8), *Stroke Order* (D1–E3), and *Write Characters* (F).

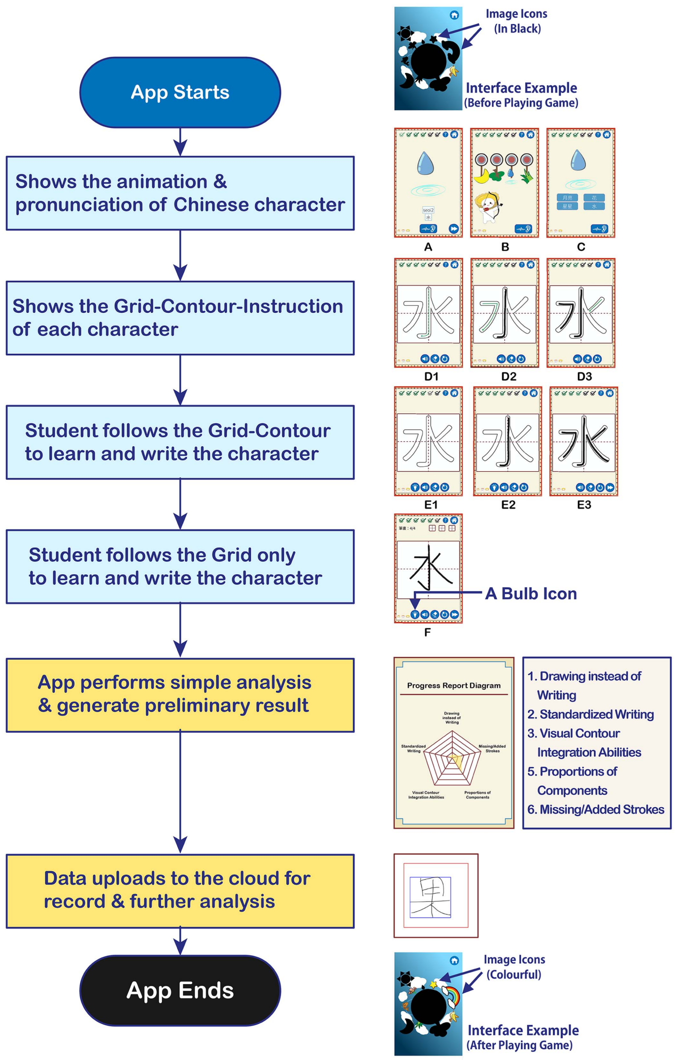


Fig. 8. Pictorial description of the learning flow and six types of games according to the learning framework in Fig. 7.

1) *Stroke Order—Grid+Contours+Instructions:* We designed a feature that provides instructions on the next stroke to be drawn by showing a green line with an arrow, as shown in D1–D3 on the right-hand side of Fig. 8. The arrow indicates the end of the stroke. The purpose is to teach students the stroke order, with which they can quickly memorize the handwriting, even if they are unfamiliar with certain characters.
For visual assistance, we provide the full Chinese character with an outline in black color. Students can easily spot which Chinese character they are going to write. When learning Chinese handwriting, the sequence of strokes is essential to help students memorize the character construction. So, we use arrows to indicate the direction of strokes. If students do not interact with the screen for 10 seconds, the stroke twinkles three times to attract students' attention. After writing the correct stroke, a unique sound effect motivates students to keep learning.
2) *Write Characters—Grid+Contours:* We create the character contours to draw. This additional feature helps students draw the characters with the correct length for each stroke and, hence, better proportions. If students forget the stroke orders, they can press the "Bulb" icon (F in Fig. 8) to visualize the hints. The purpose is to strengthen students' memory on the stroke, component ratio, and standardized writing.
We remove the stroke sequence indication in this step to facilitate students' learning. If students do not interact with the screen for 10 seconds, one stroke twinkles thrice to attract their attention and motivate them to recall the stroke order. After writing the correct stroke, a unique sound effect motivates students to keep learning.
3) *Write Characters—Grid Only:* The Grid only stage shows a grid on the drawing panel. The grid is to help students write in the right proportion and is reminiscent of typical Chinese copybooks. The purpose is to let students retrieve their memory.
We only provide students with a writing frame to write the full Chinese character. Students are required to write three times for better memory retention. If students do not interact with the screen for 10 seconds, a full character with stroke order indicators will pop up for 3 seconds. The purpose is to help students to convert short-term memory to long-term memory. After writing all three Chinese characters, there is a "cheering" sound effect to motivate students to keep learning.

We developed the learning application using Unity and C# (the primary programming language). The gamified learning environment on touchscreen employs large icons to deliver user-friendly learning contents. The study used a $2 \times 3 \times 37$ factorial design. The first independent variable (between subjects) is *Dyslexia* {Yes, No}. The other two (within ubjects) are the *Application Design* {*Grid, Grid+Contours, Grid+Contours+Instructions*} and the *Character*. The orders of the *Application Design* and *Character* are randomized across students. The first row on the right-hand side of Fig. 8 shows an example of the interface before playing the game. All icons in the interface corresponding to Chinese characters are in black, which is clickable. After learning the chosen Chinese character, the corresponding icon changes from black to colorful, as depicted by the interface at the bottom of Fig. 8. Each Chinese character follows the same order, i.e.,

1) *Grid+Contours+Instructions*,
2) *Grid+Contours*,
3) *Grid Only*.

We used 37 traditional Chinese characters in the study, categorized into three difficulty levels, as shown in Fig. 9 . Level 1 implies the most manageable level in our study. Level 2 corresponds to the middle level. Finally, level 4 denotes the highest difficulty level. The levels of difficulty are in line with the database of *A Study of the Chinese Characters Recommended* for the subject of Chinese Language in primary schools [75].

Students learn the characters one by one. Each week, we release one set of Chinese characters to the students. The most accessible characters are released first, followed by the more

Week	Character	English	Stroke	Grade	Level of Difficulty	
					Difficulty	Average
1	小	small	3	1	184	705
1	子	son	3	1	334	
1	羊	sheep	6	1	481	
1	蛇	snake	11	4	1977	
1	貓	cat	16	1	549	
2	小	small	3	1	184	706
2	大	big	3	1	196	
2	狗	dog	8	1	973	
2	蛇	snake	11	4	1977	
2	象	elephant	12	1	355	
2	貓	cat	16	1	549	
3	子	son	3	1	334	739
3	牛	cow	4	1	556	
3	羊	sheep	6	1	481	
3	虎	tiger	8	1	658	
3	狗	dog	8	1	973	
3	馬	horse	10	1	134	
3	蛇	snake	11	4	1977	
3	獅	lion	13	2	1448	
3	鴨	duck	16	1	90	
4	子	son	3	1	334	820
4	牛	cow	4	1	556	
4	虎	tiger	8	1	658	
4	馬	horse	10	1	134	
4	鹿	deer	11	2	1597	
4	猴	monkey	12	2	1564	
4	獅	lion	13	2	1448	
4	豬	pig	15	2	266	
5	小	small	3	1	184	904
5	牛	cow	4	1	556	
5	狗	dog	8	1	973	
5	鹿	deer	11	2	1597	
5	猴	monkey	12	2	1564	
5	貓	cat	16	1	549	
6	丁	person	2	1	1238	786
6	三	three	3	1	1099	
6	水	water	4	1	61	
6	文	word	4	1	301	
6	汁	juice	5	1	952	
6	布	fabric	5	1	1084	
6	奶	milk	5	1	1572	
6	年	year	6	1	261	
6	汽	vapour	7	2	178	
6	果	fruit	8	1	609	
6	治	rule	8	2	1042	
6	糖	candy	16	2	228	
6	糕	cake	16	2	1598	
7	力	force	2	1	679	779
7	月	moon	4	1	71	
7	文	word	4	1	301	
7	巧	skilful	5	2	346	
7	克	competent	7	4	1007	
7	兔	rabbit	8	1	1563	
7	餅	cookie	14	2	1483	
7	粽	rice dumpling	14	/	/	

Fig. 9. List of Chinese characters used in the study with their translation, number of strokes, grades, and difficulty levels.

complicated ones in subsequent weeks. Students can simultaneously work with an old and new set of Chinese characters. All students are assigned the same Chinese characters in the same week. Once a game level is completed, audio prompts inform students of the correct answer.

In total, 23 characters are with the level 1 difficulty, which students should be familiar with after kindergarten, 11 characters belong to level 2, equivalent to the primary two levels, and the last three characters are in level 4. We chose characters with two to 16 strokes. In addition, 15 characters are considered "single" characters (no radical/critical), and 22 are compound characters (with a radical or critical). The list of stimuli, with their meanings, levels, and the number of strokes, is shown in Fig. 9. Because of the COVID-19 situation, the planned ten-week trial was shortened to a several-week study. As a result, we collected less data on handwriting images. Overall, we gathered 2567 samples of handwriting images: 641 for the *Grid+Contours+Instructions* design, 590 for the *Grid+Contours* design, and 1336 for the *Grid Only* design. We screened out the data with null end time, uncompleted games or no action was completed. Finally, we obtained 742 samples of handwriting images: 187 for *Grid+Contours+Instructions*, 185 for *Grid+Contours*, and 555 for *Grid Only*.

IV. Experiment

A. Participants and Procedures

We recruited 20 students (ten male and ten female) aged six to eight from a local primary school in Hong Kong. The inclusion criteria for students to participate in this study were:

1) Studying in grade 1 or grade 2.
2) Being able to read and write traditional Chinese characters.
3) No other medical or physical disabilities that might interfere with handwriting abilities.

In total, six participants were in grade 1, and 14 were in grade 2. Among the participants, eight (1 in grade 1 and 7 in grade 2) were diagnosed with dyslexia with explicit writing problems and were pre-screened by teachers. Before the experiment, we obtained informed consent from the students' parents.

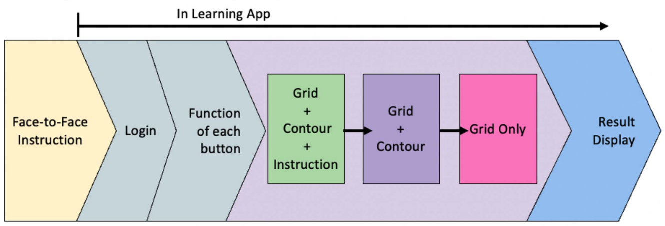
Before the experiment, students have a 10-min face-to-face training, instructing them on the function of each button and how to play the game. Then, the instructors help students log in to the application. Finally, students play the games, after which they can review their performance.

For each experiment, students first went through the training [see Fig. 10(a)]. Then, all students learned how to write a sample character with *Grid+Contours+Instruction*. After that, students tried to write the character independently with *Grid+Contours* and finally with *Grid Only*. The iPad was put either on the student's desk or a frame. Fig. 10(b) demonstrates the whole study procedure. We did not provide any remuneration to the participants.

B. Data Collection and Evaluation Metrics

We built a database system to collect user data, such as the time students need to write each Chinese character. The start time is when students enter the game by pressing the game icon. The end time is when students press the completion icon to complete the game. The variable was the *time* to write a specific character with the five-keys criterion, i.e., *visual contour integration abilities*, *standardized writing*, *missing/added strokes*, *drawing instead of writing* and *proportions of components*. We used a *writing score*, which has an aggregated measure ranging from 0 to 5 and is computed based on the five-keys criterion.

(a) The participants were working on the app. Faces are blacked out to preserve the anonymity of the students.



(b) A visual overview of the study procedure. The yellow box denotes the preparation task for participants; the grey boxes are device-based user activities primarily for the preparation stage, the boxes inside the purple-coloured frame are core learning materials, and the rightmost box in blue shows meta activity.

Fig. 10. Overview of the study procedure and the participants.

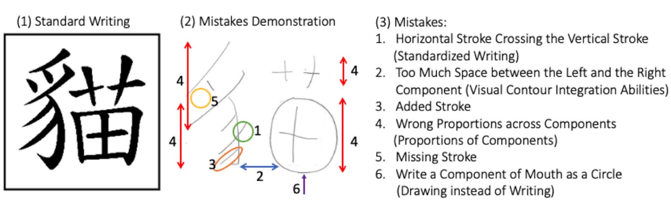


Fig. 11. Examples of mistakes for Drawing Instead of Writing, Visual Contour Integration Abilities, Proportions of Components, Components, and Missing/Added Strokes. (1) Standard Writing. (2) Student's writing. (3) Mistakes.

A linguistic student with an education degree from a university assessed the writing score. The assessor was given the task after the seven-week study and knew which week the subject made the handwriting. The assessor was well trained and followed a list of criteria with samples during the assessment. The assessment was held for four months. A professional randomly assessed 10% of the Chinese characters to ensure an objective, consistent, and without-bias assessment. An example of the assessment is shown in Fig. 11. The evaluation metrics were developed by a local research team [74]. We adopt this set of evaluation metrics because they are more suitable for traditional Chinese analysis than other evaluation metrics [30], [76], [77], [78]. In the following, we introduce the five-keys criterion.

1) Drawing Instead of Writing: Many students with dyslexia have trouble writing and always treat writing Chinese characters like drawing pictures [79]. According to dyslexia and the Chinese Language in Singapore [80], children with dyslexia tend to draw Chinese characters like pictures. When doing so, children tend to go over the same strokes multiple times as if they are drawing. Students are expected to write each character's stroke once when writing Chinese characters. The highest score is 1, the middle score is 0.5, and the lowest is 0.

2) Standardized Writing: Standardized writing is defined by EDB,[1] which provides standard writing order, appropriate position of components, and proportioning of radicals. Teachers use this standard to teach students. However, for the students who use nonstandardized writing, their characters may still be understandable for those with sufficient morpheme knowledge in Chinese. Therefore, the highest score is 1, the middle score is 0.5, and the lowest is 0.

3) Visual Contour Integration Abilities: Writing Chinese characters demands more on the visual contour integration abilities [81]. In terms of visual discrimination of character formation and position of strokes [82], the writing proficiency is more complex than those in English, as well as the spatial relationship in writing legible characters with the appropriate position of components and proportioning of radicals [78]. Students with dyslexia manifest persistent difficulties in acquiring basic writing skills. They may show poor character formation and lack of proportionality in writing the components of radicals at the character level [83]. The highest score is 1, the middle score is 0.5, and the lowest is 0.

4) Proportions of Components: Students with dyslexia may have difficulty identifying the proportionate size among components of a character [84]. As a result, students may need help when they plan for writing. An example can be seen in Fig. 11, where the height of the two components is incorrect, leading to a slight proportion issue. The highest score is 1, the middle score is 0.5, and the lowest is 0.

5) Missing/Added Strokes: Chinese character writing includes a set of standardized rules, such as the proper position, length, and direction of a line. Stroke knowledge is the foundation of handwriting skills, which provides basic information on how to compose characters. Stroke knowledge also affects children's literacy development [85]. Missing or additional strokes can affect the character's meaning. Many Chinese characters are similar in writing but different in meaning, e.g., 天 (sky) and 大 (big). Stroke issues are found to be associated with poor visual discrimination skills and visual sequential and spatial memory [77]. The highest score is 1, and the lowest score is 0.

V. Findings

In this section, we summarize the key findings of this research.

A. Writing

We performed a Chi-square test to analyze the scores of the handwriting images, with validation by Fisher's Exact test. Students without dyslexia had statistically significant results in *Drawing instead of Writing, Standardized Writing, Visual*

[1] [Online]. Available: https://www.edbchinese.hk/lexlist/

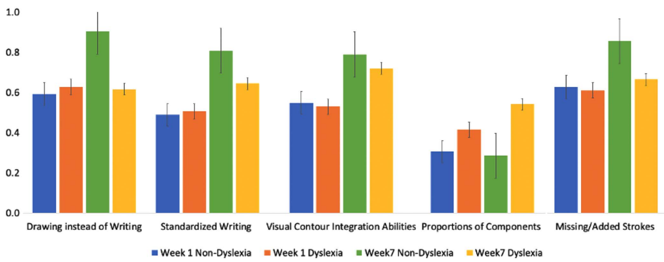


Fig. 12. Handwritten results for week 1 and week 7 from five evaluation metrics.

Contour Integration Abilities and *Missing/Added Strokes*. Students with dyslexia also had statistically significant results in *Standardized Writing, Visual Contour Integration Abilities,* and *Proportions of Components*, as shown in Fig. 12. Learning Chinese characters is a process of scaffolding [86]. If students have a solid foundation, it is easier to build their Chinese literacy ability incrementally.

1) Condition 1—Grid+contours+instructions: Students without dyslexia had no statistically significant improvement, whereas students with dyslexia had statistically significant results. The average score of students without dyslexia increased by 26.01%, from 3.54 in the first week to 4.46 in the seventh week. The association is statistically insignificant, $X^2(30) = 42.80$, $p = 0.061$. The average score of students with dyslexia increased by 55.52%, from 2.80 in the first week to 4.36 in the seventh week. The association is statistically significant, $X^2(30) = 197.29$, $p < 0.001$.

2) Condition 2—Grid+contours: Both groups had statistically significant results. The average score of students without dyslexia increased by 24.14%, from 3.71 in the first week to 4.60 in the seventh week. The association is statistically significant, $X^2(30) = 197.29$, $p < 0.001$. The average score of students with dyslexia increased by 48.25%, from 3.16 in the first week to 4.69 in the seventh week. The association is statistically significant, $X^2(30) = 197.29$, $p < 0.001$

3) Condition 3—Grid Only: Students without dyslexia have no statistically significant improvement, whereas students with dyslexia have statistically significant improvement. The average score of students without dyslexia increased by 18.57%, from 2.69 in the first week to 3.19 in the seventh week. The association is statistically significant, $X^2(80) = 106.09$, $p = 0.027$. The average score of students with dyslexia increased by 42.15%, from 2.57 in the first week to 3.65 in the seventh week. The association is statistically significant, $X^2(30) = 163.19$, $p < 0.001$.

4) Drawing Instead of Writing: Students without dyslexia had statistically significant results, whereas students with dyslexia had no statistically significant improvement. The average score of students without dyslexia increased by 52.60%, from 0.59 in the first week to 0.90 in the seventh week. The association is statistically significant, $X^2(6) = 28.24$, $p < 0.001$. The average score of students with dyslexia decreased by 1.69%, from 0.63 in the first week to 0.62 in the seventh week. The association is statistically insignificant, $X^2(6) = 6.31$, $p = 0.389$.

5) Standardized Writing: Students without dyslexia had statistically significant results, whereas students with dyslexia had no statistically significant improvement. The average score of students without dyslexia increased by 65.52%, from 0.49 in the first week to 0.81 in the seventh week. The association is statistically significant, $X^2(9) = 32.97, p < 0.001$. The average score of students with dyslexia increased by 27.55%, from 0.51 in the first week to 0.65 in the seventh week. The association is statistically insignificant, $X^2(9) = 4.93$, $p = 0.55$.

6) Visual Contour Integration Abilities: Students without dyslexia had statistically significant results, whereas students with dyslexia had no statistically significant improvement. The average score of students without dyslexia increased by 43.80%, from 0.55 in the first week to 0.79 in the seventh week. The association is statistically significant, $X^2(4) = 25.39$, $p < 0.001$. The average score of students with dyslexia increased 35.49%, from 0.53 in the first week to 0.72 in the seventh week. The association is statistically insignificant, $X^2(2) = 0.457$, $p = 0.80$.

7) Proportions of Components: Students without dyslexia had statistically significant results, whereas had no statistically significant improvement. The average score of students without dyslexia decreased by 6.63%, from 0.31 in the first week to 0.29 in the seventh week. The association is statistically significant, $X^2(4) = 27.39$, $p < 0.001$. The average score of students with dyslexia increased by 30.33%, from 0.42 in the first week to 0.54 in the seventh week. The association is statistically insignificant, $X^2(4) = 6.102$, $p = 0.19$.

8) Missing/Added Strokes: Students without dyslexia had statistically significant results, whereas students with dyslexia had no statistically significant improvement. The average score of students without dyslexia increased 36.40%, from 0.63 in the first week to 0.86 in the seventh week. The association is statistically significant, $X^2(6) = 54.76$, $p < 0.001$. The average score of students with dyslexia increased by 8.97%, from 0.611 in the first week to 0.67 in the seventh week. The association is statistically insignificant, $X^2(2) = 5.71$, $p = 0.058$.

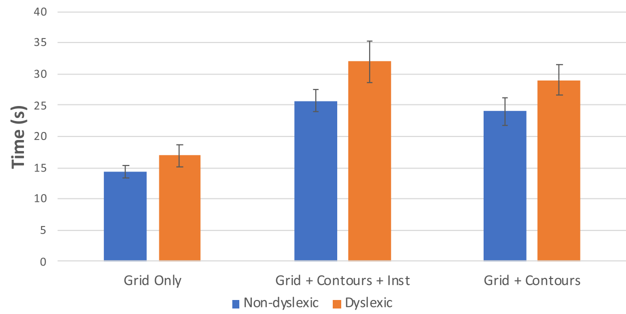
B. Time

We found a significant main effect of students with dyslexia on average time ($F_{1,9469} = 33.44$, $p < .0001$). Students with dyslexia on average were slower ($M = 23.39$ s, CI = $[22.02; 24.77]$) than students without dyslexia ($M = 19.47$ s, CI = $[18.56; 20.38]$). We also observed that the complexity of Chinese characters has a strong correlation with the writing time for students with dyslexia ($F_{38,213304} = 19.82$, $p < .0001$). Different designs also strongly impacted the writing time ($F_{2,76354} = 134.81$, $p < .0001$).

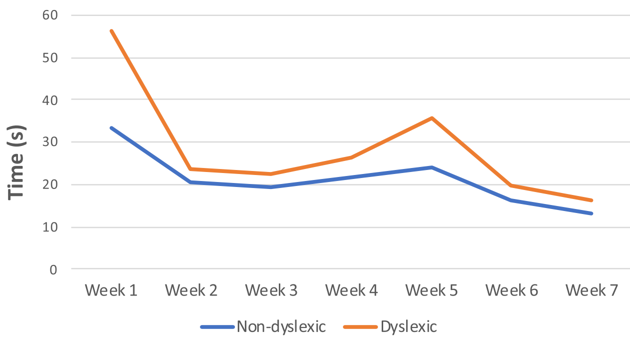
Students were faster with the *Grid Only* design ($M = 15.40$ s, CI = $[14.49; 16.31]$), followed by *Grid+Contours* ($M = 26.06$ s, CI = $[24.39; 27.73]$) and *Grid+Contours+Instructions* ($M = 28.13$ s, CI $[26.44;\ 29.83]$). Pairwise comparisons showed significant differences between *Grid Only* and *Grid+ Contours* and the other two (both $p < .0001$). A summary of the results is shown in Fig. 13(a).

C. Paper-Based Test

We invited six students to take part in the paper-based test, including three students with dyslexia (*Student D, Student E,*



(a) The average writing time for students with and without dyslexia across our application designs. Error bars show .95 confidence intervals.



(b) The average writing time for students with and without dyslexia across different weeks.

Fig. 13. Comparison of the writing time between students with and without dyslexia.

and Student F) and three students without dyslexia (*Student A, Student B, and Student C*). The test was the same as that in the application. For paper-based tests, students wanted to keep their classmates from knowing their performance. Students turned their tests over and placed them at the bottom of all submissions. *Student E* (pseudonym: Tom) saw another student complete all the words and burst into tears. Tom told us he could not write most characters, but his classmate could. So he was upset and cried. Tom's experience may be different when using digital learning tools. At least, when students submit the tests, their self-esteem will not be affected.

For the paper-based test, students without dyslexia were more motivated than those with dyslexia. Students without dyslexia could write most Chinese characters, but students with dyslexia could not. Students with dyslexia are more likely to lose motivation. As seen from Fig. 14, *Student D* could write most Chinese characters. However, six out of seven were incorrect. *Student D* was impatient in the later part of the test and started doodling (i.e., denoted in the blue circles). *Student E* could only write one Chinese character and left the rest of the boxes blank. *Student F* could not write any Chinese characters. However, we could see that *Student F* tried to write the first Chinese character. *Student F* also got impatient and wrote a lot of *crosses* on the paper. This situation may not happen with digital learning tools because when students are unmotivated, the system can detect and cheer them up with animations. In addition, the system can pop up instructions to guide students.

D. Feedback

We interviewed another student without dyslexia (pseudonym: Jack). Jack told us he liked the writing parts because he could follow the stroke order to write. However, when Jack wrote a wrong stroke, the application would give a sound effect indicating "the wrong stroke." Jack wrote a few strokes wrong and heard the "wrong" sound effect continuously, which made Jack unhappy. He suggested we could use the "try again" or "add oil" (i.e., an expression of encouragement in Cantonese) instead of the "wrong" sound effect. Jack also mentioned that having a sound effect for each writing stroke was annoying.

We also interviewed a student with dyslexia (pseudonym: Jane). Jane told us she enjoyed using our application because the application's design is cute. Moreover, she could follow the stroke instruction to learn independently and write as often as she liked. Nevertheless, Jane told us she could not hear the sound effect and pronunciation. Then, we asked Jane to interact with the iPad again and found that Jane did not know how to set the volume on the iPad.

We know from the interview that not all students have experience using tablets. A good visual design can significantly stimulate students' autonomous learning abilities. We should clarify the instruction and arrange for more instructors to guide the students during informal learning. The hardware (cases of tablets) is also essential to deliver a comfortable environment for students in informal learning.

VI. Discussion

A. Mobile Application to Help Students With Dyslexia

Overall, the application positively affects students with dyslexia. The improvement of students with dyslexia is more recognizable than students without dyslexia. Although students with dyslexia may lag at the beginning [87], [88], and we observed no difference between the two groups once they built a solid foundation after training with the application [89], [90], [91]. In addition, the learning success of students with dyslexia is sometimes slowed down by working memory problems [92]. A fun way can strengthen students' working memory. For example, Dyslexia Quest [93] used specific games to focus on just one letter sound, e.g., *p* and *s*. Accordingly, after students finish learning a Chinese character in the developed application, a cartoon character will pop up, accompanied by sound effects of clapping and cheering [94], [95]. Students with dyslexia learn more efficiently when the material is presented visually. They achieve more successes interacting with the learning material kinesthetically [96].

B. Systematic Studies on Chinese Character Learning

A total of two groups of students significantly improved in three writing conditions. However, students with dyslexia need more time to consolidate their memory and knowledge [95], [97]. Maehler et al. [98] developed an adaptive training program to improve working memory capacity and operational efficiency for students with dyslexia. Their system automatically adjusted the difficulty levels throughout the training to enable every child

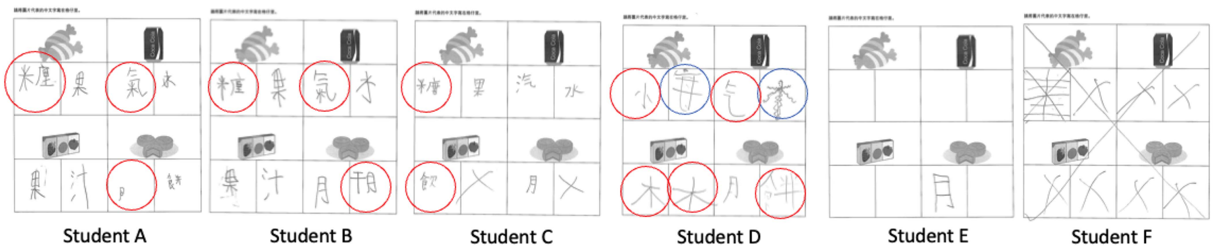


Fig. 14. Paper-based handwriting test. *Student A, Student B, and Student C* are students without dyslexia, whereas *Student D, Student E, and Student F* are students with dyslexia. Students only know their mistakes if teachers guide them when they miswrite a Chinese character. Students with dyslexia are easier to demotivate in learning Chinese characters. The red circle depicts the incorrectly written Chinese characters. The blue circle denotes the doodling.

to work according to their level. Also, their training program implemented a reward system to motivate students to participate in the training. Similarly, our app also adopted the adaptive training. When students conduct a few trials incorrectly, the app can automatically detect their problems and provide the students with hints. Therefore, our app can adjust the difficulty levels and allow students to control their learning progress and speed according to their ability.

C. *Design for Learning At Scale*

According to the design guideline [99], graphics should relate to the learning material and not distract users from the content. When designing our app, we kept the UI plain and straightforward. First, buttons with the same function were designed in the same shape so that students can achieve enhanced learnability due to the similar metaphor [100]. They can remember the function of each shape. In our application (see Fig. 2), the circular shape of buttons is regarded as functional. Second, functional cues are carefully provided. Students with dyslexia encounter more problems and difficulties in Chinese literacy. Hence, using cues can help students with dyslexia learn at scale [101].

Students with dyslexia can enhance memory with images [102], [103] and sounds [104] and learn new characters through simple games. So, we integrated images, sound effects, and pronunciations to motivate the students to learn [105], [106]. Furthermore, the levels of handwriting games range from simple to complex.

Students with dyslexia are reluctant to practice repeatedly [107]. The application design not only asks the students to enhance their memory through repeated practice but also links up the pictographs and the pronunciation of Chinese characters. We provide students with three learning conditions in writing practice, which is an instructional strategy similar to mastery learning [108], requiring students to acquire a certain prerequisite knowledge before learning subsequent knowledge [109]. As a result, students with dyslexia can potentially convert their short-term memory to long-term memory, preventing them from giving up learning once they forget how to write.

D. *Limitations*

Initially, we planned to conduct ten weeks of pilot sessions in this study. However, due to the sudden emergence of COVID-19, the pilot sessions were reduced to seven weeks, which may affect some of the students' performance. Also, the current sample size is relatively small because very limited students with dyslexia are prescreened at an early age, i.e., below ten years old, in Hong Kong, due to the long waiting time for assessment. Furthermore, due to the pandemic, we could not collect samples from the control groups, i.e., students learning the same content in a traditional classroom.

VII. Conclusion

This article introduced an application to help students with and without dyslexia learn Chinese handwriting. The study was done in a unique context, where students learn Cantonese without prior exposure to any alphabetical script. It was observed that the developed application could help shorten the time students with dyslexia need to write a given character. Furthermore, students with dyslexia had statistically significant improvement in standardized writing, visual contour integration abilities, and proportions of components.

In the future, we will run the experiment with a control group and an experimental group and experiment in a larger scale. The control group will go through the traditional classroom study, and the experimental group will learn with our application. The purpose is to check whether the positive results are due to intervention design or repeated practice. Also, we will extend the proposed approach to simplified Chinese and Mandarin. Similarly, our approach could be transferred to other languages that use writing systems derived from Chinese characters or use similar writing systems, e.g., Japanese and Korean.

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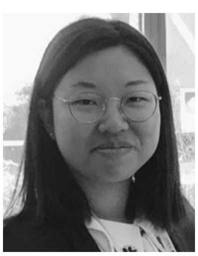


Ka-Yan Fung received the M.Phil. degree in technology, leadership, and entrepreneurship (TLE) from the Hong Kong University of Science and Technology, Hong Kong, in 2021 and the M.Phil. degree in contemporary east Asian studies from Duisburg-Essen University, Duisburg, Germany, in 2018. She is currently working toward the Ph.D. degree in human–computer interaction in the individualized interdisciplinary program with the Hong Kong University of Science and Technology.

Her research interests include specific learning disabilities (SLDs), human–computer interaction (HCI), human–robot interaction (HRI), data visualization, and open education.

Simon Tangi Perrault received the Ph.D. degree in computer science from Telecom ParisTech, Paris, France, in 2013.

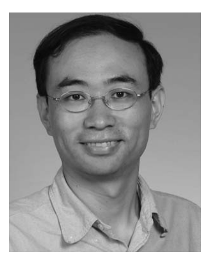
He was a Visiting Professor at the Korean Advanced Institute of Science and Technology, Daejeon, South Korea, and Assistant Professor with Yale-NUS College, Singapore. He is currently an Assistant Professor in information systems technology and design with the Singapore University of Technology and Design.

Lik-Hang Lee received the B.Eng. degree in logistics engineering and supply chain management and M.Phil. degree in industrial and manufacturing systems engineering from the University of Hong Kong, Hong Kong, and the Ph.D. degree in computer science and engineering from The Hong Kong University of Science and Technology, Hong Kong, in 2011, 2014, 2019, respectively.

He is currently an Assistant Professor (tenure-track) with Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea. He is also the Director of the Augmented Reality and Media Laboratory, KAIST. He has built and designed various human-centric computing specializing in augmented and virtual realities (AR/VR). He is also the Founder of an AR startup company, promoting AR-driven education and serving more than 100 Hong Kong and Macau schools.

Kwong-Chiu Fung received the M.Phil. degree in technology leadership and entrepreneurship (TLE) from the Hong Kong University of Science and Technology, Hong Kong, where he is currently working toward the Ph.D. degree in individualized interdisciplinary program.

His research interests include computer vision, data analytics, robotics, and assistive technology.



Shenghui Song (Senior Member, IEEE) received the B.Eng. and M.Eng. degrees from Tianjin University, in 2000 and 2002 and Ph.D. degree from University of Hong Kong in 2006. He is currently an Assistant Professor jointly appointed by the Division of Integrative Systems and Design (ISD) and the Department of Electronic and Computer Engineering (ECE), Hong Kong University of Science and Technology (HKUST), Hong Kong. His research interests include wireless communications and machine learning with current focus on distributed intelligence, machine learning for communications, integrated sensing and communication, and information theory.

Dr. Song was named the Exemplary Reviewer for IEEE COMMUNICATIONS LETTERand was the Tutorial Program Co-Chairs of the 2022 IEEE International Mediterranean Conference on Communications and Networking. He is also interested in the research on engineering education and was an Associate Editor for IEEE TRANSACTIONS ON EDUCATION(2013–2022). He was the recipient of several teaching awards at HKUST, including the Michael G. Gale Medal for Distinguished Teaching in 2018, Best Ten Lecturers in 2013, 2015, and 2017, School of Engineering Distinguished Teaching Award in 2012, Teachers I Like Award in 2013, 2015, 2016, and 2017, and M.Sc. (Telecom) Teaching Excellent Appreciation Award in 2021. He was one of the honorees of the Third Faculty Recognition at HKUST in 2021.