Can Underprivileged Children Learn Effectively at Home? A Six-Month Study of Game-Based Traditional Chinese Learning During the Pandemic Lockdown

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***Abstract*—The COVID-19 pandemic has suspended physical classes and influenced students from underprivileged groups more seriously due to their poor living conditions and digital disadvantages. To understand the impact of the constrained learning, we conducted a study on game-based learning to examine the effectiveness of computer-aided and autonomous learning of traditional Chinese by underprivileged students. From December 2020 to May 2021, we collected 3245 quiz results from 26 underprivileged students over six months. The quizzes systematically covered the fundamentals of learning traditional Chinese in six aspects, i.e., literacy, orthography, phonology, morphology, speaking, and writing. We analyzed the results to understand the learning efficacy of students. Remarkably, students can significantly improve their skills in literacy and phonology through unsupervised game-based learning. Furthermore, by parsing the writing tasks, we observe substantial improvements among 7 out of 13 common types of writing mistakes. Our study provides a critical lens to understand the design opportunities of game-based learning without direct supervision.**

***Index Terms*—Autonomous learning, COVID-19, computer-assisted language learning (CALL), game-based learning, gamification, mobile learning.**

I. Introduction

Since the COVID-19 outbreak, numerous preventive measures have been implemented, which have significantly influenced various aspects of our daily life. In the education sector, lockdown measures have led to a long period of physical class suspension around the globe. A survey by UNESCO [1] showed that education is one of the most severely impacted sectors where no less than one billion students suffered from this challenging circumstance. Although the development of information technology allows learners to learn whenever and wherever they want [2], [3], underprivileged children may not be able to benefit from this advancement. During the pandemic, the number of underprivileged children (under 18) in Hong Kong rose from 237 100 in 2018 to 258 600 in 2020 [4]. Poor living conditions and digital disadvantages [5] affect underprivileged children's learning at home during the pandemic lockdown. The average living space per person in Hong Kong is 161 square inches, and subdivided flats are even smaller [6] Besides, underprivileged families cannot support children's homeschooling. Over 75% of children are affected by slow internet speed, and 22.3% of children's digital devices are too old to support the most updated learning software [7]. Learning during the pandemic widened the gap between poor and wealthy schoolchildren due to inadequate hardware (e.g., tablets) and Internet access (e.g., Wifi) for online learning. The academic performance of more than half of students has declined due to online learning [8], reducing their learning motivation and, hence, creating a vicious circle.

In this research, we focus on underprivileged students and keep track of their learning performance with autonomous and computer-assisted language learning (CALL) for six months. The authors are interested in understanding the capability of online learning in assisting underprivileged primary schoolchildren in learning traditional Chinese (an official language in Hong Kong). The research questions (RQs) we want to answer include the following: 1) How effectively can students learn the six fundamentals of traditional Chinese, namely literacy, orthography, phonology, morphology, speaking, and writing? 2) What are the limitations of learning such fundamentals through mobile apps? 3) What are the difficulties of underprivileged students in learning the six fundamentals through games? 4) What are the user retention rates?

We conducted a longitudinal study to capture users' behavior and performance of learning traditional Chinese in the wild. Without the teacher's supervision, students used a mobile app to learn traditional Chinese from December 2020 to May 2021 (6 months) at home, as shown in Fig. 1. Since existing learning apps do not cover the six fundamental aspects of traditional

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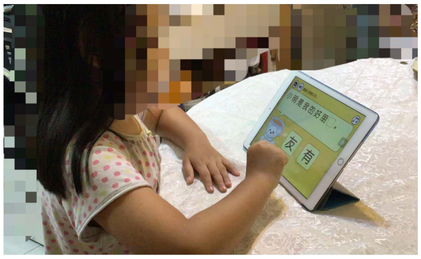

Fig. 1. Participant was working on the Morphological Awareness game (Type 4) at home.

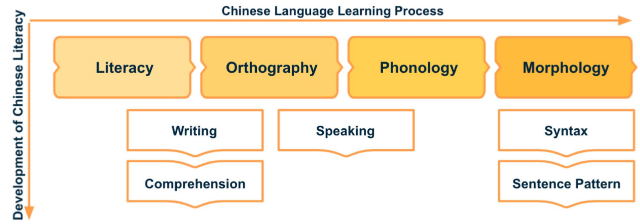

Fig. 2. Framework of Chinese language learning process. It is important to note that we focus on literacy, orthography, phonology, morphology, speaking, and writing.

Chinese (see Section IV for more details about the six fundamentals), we designed our own app. The participants are considered disadvantaged groups, who usually live in government-sponsored public housing estates with cramped and crowded environments (i.e., 3-4 family members in 30 m^2). The participants can barely concentrate on learning in such a constrained environment. The situation worsens when some students do not have a dedicated desk for their studies and need to complete schoolwork on their beds [9].

Over the six-month study period, we collected 3245 quiz results from 26 effective respondents (i.e., primary school children studying in grades 1–3). We observed significant improvements in two fundamentals, i.e., literacy and phonology. To keep track of the common writing mistakes, we defined 13 labels to measure students' writing performance. It was observed that students could improve in 7 out of the 13 writing mistakes, namely Noncharacters, Directionality, Transposition, Stroke Insertion/Deletion, Broken Stroke Errors, Incorrect Stroke Type, and Component Replacement.

The rest of this article is organized as follows. We first review the related works in Section II. Section III describes the design of the learning apps, and the experiment is introduced in Section IV. Next, we report our findings in Section V, and Section VI provides some discussions. Finally, Section VII concludes this article.

II. Related Works

Human–computer interaction (HCI) researchers have paid continuous efforts to design HCI-aided pedagogy [10], [11], [12], [13], [14], [15]. In recent years, more research works focused on inclusive design to meet the special education needs [16], support disabled learners [17], and tutor low-income kids [18]. With the advent of the COVID-19 pandemic, the insufficiency of learning content delivery has recently come to light. Although online learning can be an immediate solution, researchers also pinpointed the difficulties of conducting classes remotely [19] and proposed solutions to alleviate the inconvenience for both learners and instructors [20]. However, the challenges and difficulties encountered by early-age learners from low-income families during the pandemic have yet to be well investigated.

A. Challenges in Learning Traditional Chinese at Home

Chinese is a complex language to learn due to the complex graphic configuration of Chinese characters [21], [22]. Furthermore, Chinese is a logographic script without prominent sound-script correspondence, i.e., the Chinese characters contain graphic elements without obvious pronunciation clues [21]. For instance, both 晴 (literally: sunny) "cing4" and 晴 (literally: eyes) "zing1" contain the component 晴 (literally: green) "cing1" but own different pronunciations and meanings.

The app developed in this study is characterized by the comprehensive coverage of Chinese learning in sequential stages, including 1) literacy, 2) orthography, 3) phonology, 4) morphology, 5) speaking, and 6) writing. This study serves as the first effort to systematically examine the learning of traditional Chinese by disadvantaged early-age students in-the-wild. It is important to note that the fundamental knowledge of early-age learners in traditional Chinese is weak. We pinpoint that the participants in our work are considered disadvantaged groups.

As mentioned before, the living space of underprivileged students is poor. They even do not have desks to finish their assignment at home and are surrounded by noisy environments. Also, compared with middle/high-income families, underprivileged students do not have extra resources (e.g., private tutoring, digital books, and paid online lessons) for learning, which is especially critical during the COVID-19 pandemic [23], [24]. In addition, underprivileged families are relatively less educated. The parents do not have sufficient knowledge or resources to teach their children or support their learning at home, and, even worse, some are illiterate [25]. As a result, no fewer than 80% of underprivileged families feel pressured to have their children conduct online classes at home [26].

B. Six-Dimension Design

Our app was designed to address the six fundamental dimensions of learning Chinese progressively, including 1) literacy, 2) orthography, 3) phonology, 4) morphology, 5) speaking, and 6) writing. Following the recommendations of the Education Bureau (EDB) at Hong Kong [27], [28], [29], we formulated a 2-D study, as shown in Fig. 2: 1) Chinese character recognition process and 2) the development of Chinese literacy, which aids students in incrementally establishing their understanding of Chinese. Chinese character recognition process refers to children's strategies in using orthography, phonological, and morphological cues of radicals to identify Chinese [30]. In contrast, Chinese literacy refers to students' ability to read and write Chinese [31]. Literacy development (upper left corner of Fig. 2) is notably viewed as the starting point of learning traditional Chinese. Along the horizontal axis of the Chinese Character Recognition Process, students should follow

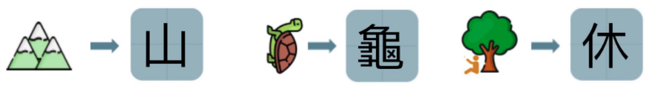

Fig. 3. Pictorial description of traditional Chinese characters. From left to right: 山 (lit. hill), 龜 (lit. turtle), and 休 (lit. rest).

a learning path that includes the acquisition of orthography, phonology, and morphology of words in sequence [32]. Orthography refers to the existing rules of printed structures [33]. By understanding the derivation of strokes and character components, students can acquire orthographic awareness and the capability of distinguishing between pseudocharacters [34].

Students generally begin with pictorial representations when studying Chinese, associating traditional Chinese characters with their pictorial descriptions, as illustrated in Fig. 3. Then, students understand the importance of composing characters by logographeme components [35]. In the Chinese writing system, logographeme units refer to a core component that is more diminutive than a radical [36]. Next, students utilize their orthographic skills to discern pseudocharacters. Finally, students can apply their orthographic knowledge to reading and vocabulary acquisition. Phonology entails the study of the pronunciation of Chinese characters. It is vital to emphasize that orthographic and phonological awareness are connected and aids the processing route toward the final stage of morphology [37]. After mastering the basics of reading, students can employ the provided framework to interpret syntax and sentence structure. The vertical axis in Fig. 2 indicates the knowledge phases of traditional Chinese vocabulary. Knowing the meaning of a sentence involves knowledge of both words and sentence structures.

After mastering the concept of word order, students can improve their traditional Chinese literacy by creating compelling words [38]. According to their semantic functions, the Chinese language highlights sentence order [39]. Consequently, acquiring word and sentence patterns may facilitate the learning progression in subsequent stages. Concurrently, students can keep on improving their writing and comprehension skills.

According to Tan et al. [40], there is a considerable correlation between children's ability to read and write Chinese [41]. Students who have previously studied the orthography, phonology, and morphology of traditional Chinese characters may be able to deconstruct characters into components and strokes and reassemble them into a square unit through writing practice [42]. In addition, with the knowledge of words and sentence patterns, repetitive writing helps reinforce students' long-term memories of Chinese character formation and assists the formation of effective linkages between visual symbols [40]. Connections can improve the precision of reading and the speed of visual processing. In conclusion, the development of Chinese literacy incorporates sequential phases of character recognition, word and sentence structure understanding, and writing and reading skills.

C. Unsupervised Chinese Learning on Mobile Devices

Educational apps can effectively stimulate students' intrinsic learning motivation [43] and encourage them to explore knowledge actively [44]. By decomposing the knowledge structure into knowledge blocks, learners can learn in fragments [45]. Moreover, educational apps can adjust the learning materials according to each student's progress, providing a personalized learning platform. Learners can create learning plans and goals, track progress, and select modules for customized learning [44].

Table I describes the available apps for learning traditional Chinese. The EDB developed a webpage game called "Book Work Reading Site" to train students' Chinese reading and writing skills by providing online reading materials, story rewriting, and Chinese language games [47]. A nongovernment organization named Heep Hong Society developed an app (Read and Write Trooper) [49] to strengthen children's listening, speaking, reading, and writing skills. Starwish Little Prince's online learning platform offers learners various Chinese word learning games, including stroke order, grapheme and component structure, radical analysis, and word learning and searching. In addition, this platform provides reports for players to track their learning progress and problems, allowing them to focus on particular areas [48]. However, the above apps do not fully cover the six fundamental learning dimensions.

D. Availability of Digital Devices and Internet Access

Government statistics indicated that over 94% of households in Hong Kong have access to the Internet at home, by PCs, smartphones, and tablets [51]. Nearly six million individuals aged 10 and above have smartphones. Most students can learn with tablets in the classroom. The Hong Kong government also provides the "Information Literacy for Hong Kong Students" learning framework for schools to develop students' knowledge and skills in information technology [28]. Therefore, in general, underprivileged children in Hong Kong have experience using tablets, which is the platform for this study.

E. Retention Rate of Underprivileged Children

Retention rate is challenging in mobile gamification-based learning [52]. One reason is that children need more time to switch from formal to informal learning [52]. Therefore, more insights into the conditions effective in promoting online learning are desirable. Furthermore, when children experience difficulties, their confidence drops, and as a result, they might lose their motivation and interest, leading to withdrawal from learning [53]. Therefore, proper teaching methods and strategies should be designed to increase students' motivation and interest to maintain retention [54].

III. Game Design

A. Six Types of Games for Six Fundamentals

According to the framework [55] shown in Fig. 2, we designed six types of games that encourage students to engage in reading, writing, listening, and speaking. The six types of games refer to Radical and Components (Type 1), Orthographic Awareness (Type 2), Phonological Awareness (Type 3), Morphological Awareness (Type 4), Speaking (Type 5), and Writing (Type 6). A pictorial description of the six-game types is shown in Fig. 4.

TABLE I
SUMMARY OF THE LEARNING APP DESIGNATED FOR TRADITIONAL CHINESE

Name	Type	Description	Literacy	Orthography	Phonology	Morphology	Speaking	Writing
Mobiles [46]	Mobile	To target early primary school students to learn Chinese characters.	✗	✓	✗	✗	✗	✓
Book Work Reading Site [47]	Web	To target student's Chinese reading and writing skills by providing them with online reading materials, story rewriting, an Chinese language game.	✗	✗	✗	✓	✗	✓
Starwish Little Prince [48]	Mobile	To offer learners various Chinese word learning games through an online learning platform.	✓	✓	✗	✗	✗	✓
Read and Write Trooper [49]	Mobile	To provide the Pre-Writing Fun Journey 2 application to train children's Writing ability.	✗	✓	✓	✓	✓	✓
Chinese Word Pool [50]	Web	To provide various in-class learning activities to help students improve their Chinese language skills.	✓	✓	✗	✓	✗	✗

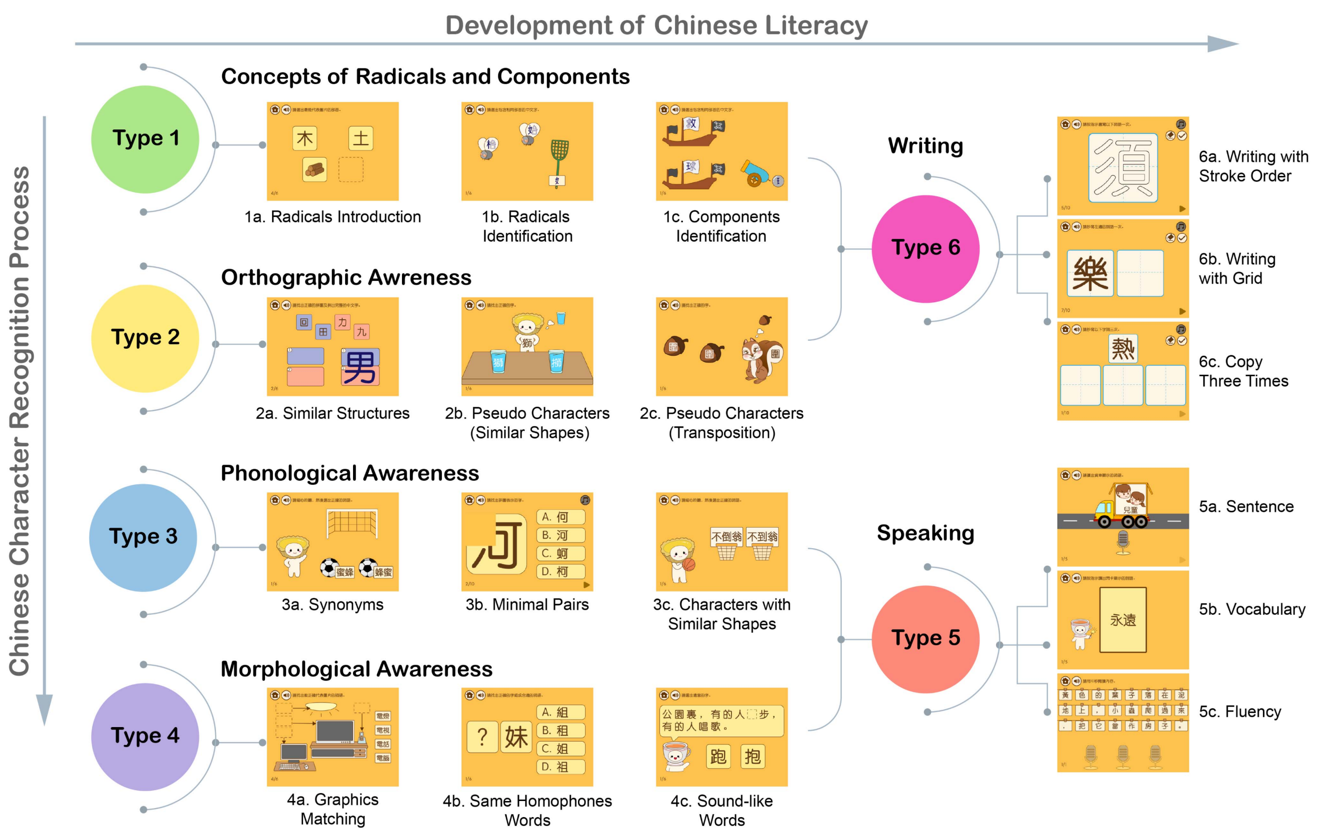

Fig. 4. Pictorial description of the six-game types that address the two learning dimensions in Fig. 2.

The designed app employs large icons to deliver user-friendly learning content. We consulted one educational psychologist, one education professional, and two primary school teachers (majoring in Chinese) when designing the games. Two straightforward choices are provided for Types 1 and 2 to motivate students to learn at the basic levels. After students complete the basics in Types 1 and 2, the difficulties in Types 3 and 4 are increased by providing up to four choices. When designing the user interfaces, we focused on improving the motivation [56] and participation [57] of students and gave them the freedom to fail in the learning process without worrying [58]. Considering the children's feelings, we used different animations and sound effects to notify them of the correctness of their input. The app also provides a function called "*read-text-aloud*" that assists students' understanding of the questions by audio. The difficulty of all questions is at the primary one's level and organized based on the level of commonness and difficulties [59].

1) *Radicals and Components (Type 1):* Mastering the knowledge of radicals and components could help students learn to read and write traditional Chinese [60]. Game Type 1 introduces Chinese radicals (see Fig. 4, 1a) to students. It also trains students to identify different traditional Chinese characters by the radicals (see Fig. 4, 1b), each with the same components (see Fig. 4, 1c).
2) *Orthographic Awareness (Type 2):* Orthographic skills govern the arrangement of the internal structure ordering. Game Type 2 aims at training students to identify characters with similar structures (see Fig. 4, 2a) or pseudocharacters [see Fig. 4, 2b (similar shapes) and 2c (transposition)].

Fig. 5. Action language. Notification of (answer) correctness follows specific game communication rules. Situation 1 (the first row) demonstrates the effect of correct answers. Situation 2 illustrates the effects of incorrect answers.

3) *Phonological Awareness (Type 3):* It provides audio clips and text options for students to match. We add synonyms (see Fig. 4, 3a), minimal pairs (see Fig. 4, 3b), and characters with similar shapes (see Fig. 4, 3c) to confuse students. In learning traditional Chinese, a significant connection exists between phonological awareness and character recognition [61], [62].
4) *Morphological Awareness (Type 4):* It refers to the knowledge of breaking down a word into smaller units, including sensitivity to homophones, lexical compounding, and generating words that contain the targeted morpheme [61]. Students have to match vocabulary with their relevant graphics (see Fig. 4, 4a). The vocabulary contains the same morphemes. Students are also required to form meaningful sentences or vocabularies by choosing the correct words among homophones or soundlike words (see Fig. 4, 4b and 4c).
5) *Speaking (Type 5):* This is an audio-based game. Students are required to read out vocabulary and sentences in Cantonese (see Fig. 4, 5a and 5b). When students read sentences aloud, they can train their fluency in expressing thoughts (see Fig. 4, 5c).
6) *Writing (Type 6):* It consists of writing practice for traditional Chinese characters. Chinese writing involves complex geometric figuration and stroke arrangement within a squared area [63]. So, the app provides stroke orders (see Fig. 4, 6a) and writing grids to assist students' writing (see Fig. 4, 6b). Students copy the same characters three consecutive times to establish the continuity of their writing (see Fig. 4, 6c) to train students' vocabulary memory [64].

B. Game-Based Design

Gamified learning theory includes four main concepts: 1) instructional content, 2) game characteristics, 3) behaviors/attitudes, and 4) learning outcomes [65]. First, instructional content is the instructions teachers use to educate students and facilitate their understanding [66]. In our work, the six types of games constitute the instructional content. Second, game characteristics are game elements used to gamify the instructional content. Bedwell et al. [67] introduced a framework of nine-game attributes that organizes game elements into categories. Using this taxonomy, we applied the action language (see Fig. 5) (e.g., notification of correctness follows specific game communication rules), conflict/challenge (i.e., the level of difficulties increases substantially to make the games more challenging), and immersion (i.e., the game adopts multiple visual and auditory simulations to make it more attractive to the children). Third, behaviors/attitudes refer to the instructional content and game characteristics that impact the behaviors and attitudes. In our work, the instructional content and game characteristics may affect the retention rates (behavior) reflecting children's engagement with the games (attitudes) [68]. Finally, learning results are the primary outcomes in the gamified learning theory, which are measured by scores and time spent.

TABLE II
BACKGROUND OF THE VALID RESPONDENTS

ID	Grade	Chinese Level	Dyslexia	Gender	Handed-ness	Age
a112	1	General	No	M	R	7
a119	1	General	No	M	R	6
a121	1	Low	No	M	R	7
a125	1	General	No	M	R	7
a127	1	General	No	F	R	7
a128	1	General	No	M	R	7
a129	1	Low	No	M	R	6
a130	1	General	No	M	R	6
a132	1	General	No	M	R	6
a133	1	General	No	M	R	7
a136	2	General	No	M	R	8
a138	2	Low	No	M	R	8
a148	2	Low	No	F	R	7
a149	2	General	No	F	R	8
a150	2	Low	No	F	R	8
a151	2	Low	No	F	L	8
a156	2	General	No	F	R	8
a158	2	Low	No	M	R	7
a159	2	Low	No	M	R	7
a160	2	Low	No	M	R	7
a161	3	Low	Yes	F	R	8
a162	3	General	Yes	M	R	8
a167	3	Low	No	M	R	8
a170	3	General	Yes	M	R	9
a173	3	General	Yes	M	R	8
a177	3	General	Yes	M	R	9

IV. EXPERIMENT

Learning a language typically requires intensive practice and tutorials with the presence of instructors [69]. In this section, we introduce the experiments designed to validate the effectiveness of unsupervised online learning.

A. Participants, Procedures, and Regulations

We initially recruited 68 students (46 males and 22 females) aged 6–9 years old ($\bar{M}$= 7.38-year-old σ= 0.93-year-old) from a local primary school in Hong Kong. As shown in Table II, 25 were in grade 1, 26 were in grade 2, and 17 were in grade 3. The inclusion criteria for students to participate in this study were 1) studying in grade 1 to grade 3, 2) being able to read and write traditional Chinese characters and speak Cantonese, 3) having no other medical or physical disabilities that might interfere with the handwriting ability and reading aloud ability,

TABLE III
DATA COLLECTION AND DATA SCREENINGS

Screening Stage	Screening Method	Total Quiz Data	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
0	Raw data	3,245	867	660	367	437	357	557
1	Screen end time was null and no action was completed	2,505	814	302	345	323	314	407
2	Screen outlier (1.5IQR)	2,372	777	292	318	264	314	407

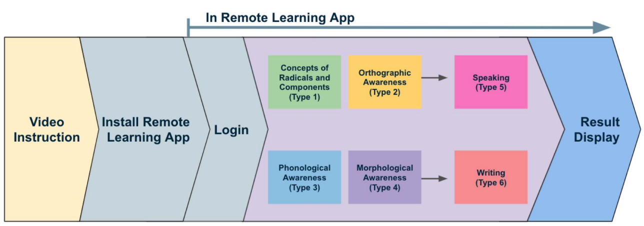

Fig. 6. Visual overview of the study procedure.

and 4) living in public housing and have no additional help at home. Based on students' school performance, their school teachers provided the information regarding the participants' Chinese levels, categorized as *low* or *general*. Also, all students have experience in using smartphones and tablets. After six months of experiments, we screened out a total of 35 students, because 33 of them did not open the apps, 3 students played the game once within six months, and 6 were inactive for five out of the six months. Eventually, we collected data from 26 students (19 males and 7 females) aged 6–9 years old ($\bar{M}=7.30$-year-old, σ=0.37-year-old). Out of the 26 students, 25 are right-handed.

Fig. 6 shows the entire procedure of this study. First, we provided video instructions for parents and students on installing the app, logging in, and playing the game. Second, the parents helped students install and log in to the app. Third, students played the games, after which they could review their results.

This study follows the following regulations: 1) The University Institutional Review Board (IRB) approved the experimental protocol. 2) Participation was entirely voluntary and based on consent. 3) We did not provide any remuneration to the participants. 4) We conducted the study under the premise of social distance. 5) We obtained informed consent from the student's parents before running the experiment.

B. Data Collection and Evaluation Metrics

We built a database to collect user data from the app. The data include the correctness rate, answer time, audio sources, and handwriting images. For the time spent, the start time is recorded once the participants enter the game by pressing the game icon while the end time is recorded when the participants press the completion icon to end the game.

1) *Radicals and Components (Type 1), Orthographic Awareness (Type 2), Phonological Awareness (Type 3), and Morphological Awareness (Type 4).* Each game consists of five minigames and one verification game question. The app selects the verification game randomly from the five minigames. Each minigame has the same weight and is worth one point. If students correctly answer the game, they get one point. Otherwise, they get zero points. If students answer the validation game incorrectly, one point is deducted. The score range is from 0 to 5 points.
As shown in Table III, initially, we collected 3245 raw quiz data. We first screened the data whose end time was null or no action was completed. After the screening, we had 1784 quiz data. Then, we took the interquartile range (1.5×IQR) to screen out outliers. The outlier's time spent was longer than 121 s. After the abovementioned strict screening, the total number of quiz data samples was 1651. We had 777 data in Radicals and Components (Type 1), 292 data in Orthographic Awareness (Type 2), 318 data in Phonological Awareness (Type 3), and 264 data in Morphological Awareness (Type 4).
2) *Speaking (Type 5).* Type 5 consists of quick naming games and sentence reading. In the quick naming games, students are required to name the image in 3 s. For sentence reading, students are given 10 s to read through the sentence and 30 s to read aloud. In the quick naming game, there are five minigames. Students earn one point for each minigame if they answer correctly. Otherwise, they get zero points. If students read the vocabulary correctly, they get one point. Otherwise, students get zero points. In sentence reading games, there are five minigames. The score range is from 0 to 3 points. We count the total number of characters in the sentences. Students who read out 90% to 100% of the sentence get three points. Students who read out 70% to 89% of the sentence get two points. If students read 50% to 69% of the sentence, they get one point. Otherwise, students get zero points. A local scholar in the special education sector designed the grading system. We collected 357 data (see Table III) and screened out those containing no content. Finally, we had 314 data in Type 5, including 247 data in quick naming and 67 data in sentence reading, respectively.
3) *Writing (Type 6).* We collected data on time students spent on each handwritten image. Each handwriting game consists of five minigames, and each carries equal weighting, covering 13 common mistakes (see Fig. 7). The score ranged from 0 to 13 points. The first author and a local scholar in the special education sector designed the grading criterion. A linguistic student and a psychology student did the grading independently. As shown in the proposed framework (see Fig. 4), Radicals and

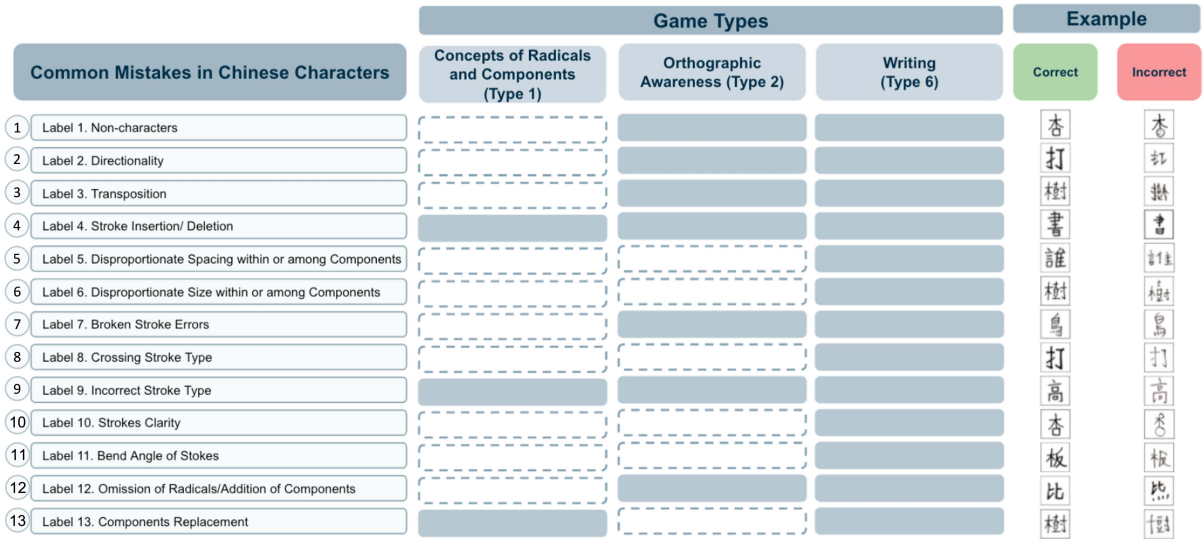

Fig. 7. Proposed framework consists of 13 common mistakes.

Components (Type 1), Orthographic Awareness (Type 2), and Writing (Type 6) are interrated, complying with the standard pedagogy of traditional Chinese. In particular, students should first identify pictorial descriptions for respective Chinese characters. Then, students begin understanding the fundamentals of characters composed of logographeme units. Subsequently, students can write traditional Chinese characters. We selected 77 traditional Chinese characters as the training materials based on the feedback from primary school teachers. We collected data for six months. However, there was no data input in the 5th month, primarily due to the Easter holiday. The 13 labels are described as follows (with examples shown in Fig. 7).

a) Label 1: Noncharacters [70]. An integral part of compound characters is graffiti or only the radicals.
b) Label 2: Directionality [71]. Part of the characters [72] or the whole character is a mirror character.
c) Label 3: Transposition [73]. There are transposition strokes or components in the characters.
d) Label 4: Stroke Insertion/Deletion [73]. There are one or more addition/deletion strokes in the characters.
e) Label 5: Disproportionate Spacing within or among Components [71]. The space inside a component or among the components is disproportionate.
f) Label 6: Disproportionate Size within or among Components [71]. The size within a component or the size of a component is disproportionate.
g) Label 7: Broken Stroke Errors [74]. A component or a single-component character is broken into multiple parts.
h) Label 8: Crossing Stroke Errors [74]. Strokes mistakenly crossed or did not cross over other strokes.
i) Label 9: Incorrect Stroke Type [73]. The wrong stroke type is written.
j) Label 10: Strokes Clarity. Strokes are concatenated, broken, or not written.
k) Label 11: Bend Angle Strokes [75]. The angle of the stroke is inclined.
l) Label 12: Omission of Radicals/Addition of Components [71]. The radical of a character is missing, or an additional component is inserted into the character.
m) Label 13: Component Replacement. The components are misplaced [76].

We collected 557 pieces of data (see Table III) and screened out the data where end time was null or with no action recorded. We then screened out the characters not written in five out of the six months. After the implementation of the strict screening criteria, the final number of data was 407 in Writing (Type 6), in which 10 traditional Chinese characters, i.e., 比 (compare), 打 (hit), 知 (know), 長 (long), 酒 (alcohol), 院 (yard), 高 (tall), 採 (pick), 須 (must), and 試 (test), were selected as remarkable examples in the following discussion (see Section V).

V. Findings

This section elaborates on the key findings related to the primary RQs to be answered in this article. We first probe the potential of learning the six fundamentals of traditional Chinese on mobile devices, i.e., what can be done? and what cannot? We also discuss the observations on speaking and writing tasks (Types 5 and 6), where writing is regarded as the ultimate stage in the learning process of most languages. The results also shed light on the challenges of retention rates and the constraints the early-age learners encountered at home.

A. Fundamentals

First, we illustrate the effectiveness of online learning concerning six learning fundamentals. Fig. 8 shows the overall performance during the six months. Table IV outlines participants' learning performance for four-game types in the 1st and 6th months. All 26 participants were counted in each type and month in the data collection. It can be observed that, for Radicals and Components (Type 1) and Phonological Awareness (Type 3), significant improvement was achieved in both the average time spent and the average scores. As shown in the

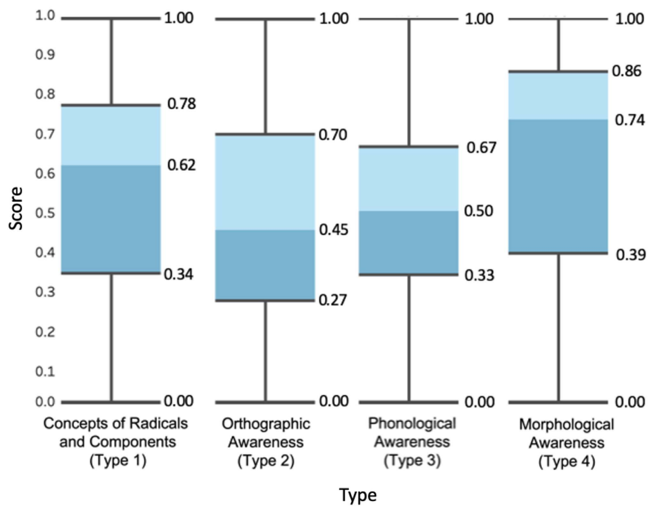

Fig. 8. Averaged score of the first four types of games in six months.

TABLE IV
PARTICIPANTS' LEARNING PERFORMANCE FOR THE FOUR-GAME TYPES IN THE 1ST AND 6TH MONTHS

Type	Month	Average Score	SD	p-value	% of Improvement
1*	1st Month	0.875	0.366	0.023	10.218
	6th Month	0.964	0.138		
2	1st Month	0.847	0.376	0.225	10.251
	6th Month	0.933	0.177		
3*	1st Month	0.744	0.446	0.045	24.263
	6th Month	0.925	0.183		
4	1st Month	0.806	0.455	0.315	12.274
	6th Month	0.904	0.272		
Type	Month	Average Time	SD	p-value	% of Improvement
1*	1st Month	51.065	37.618	0	-31.949
	6th Month	34.75	37.959		
2	1st Month	52.218	39.116	0.196	-18.505
	6th Month	42.556	26.081		
3*	1st Month	63.378	40.352	0.282	14.195
	6th Month	72.375	54.573		
4	1st Month	53.756	52.273	0.837	4.439
	6th Month	56.143	70.798		

study framework (see Fig. 2), literacy is the foundation of the Chinese recognition process. Radicals and Components (Type 1) are the cornerstones of literacy. Type 1 games can consolidate the participant's foundation, evidenced by the reduced average time spent and improved average score.

After laying a solid foundation, the participants can improve their literacy by strengthening their Orthographic Awareness (Type 2) and Writing skills (Type 6). Although the participants demonstrated a small degree of improvement in the performance of Type 2, the absence of statistical significance indicates the limitation of such games. Learning is a process of scaffolding [69]. If participants do not have a solid foundation in Orthographic Awareness (Type 2), it takes work to build writing skills (Type 6).

On the other hand, Phonological Awareness (Type 3) is the essential element in building up Morphological Awareness (Type 4) and Speaking ability (Type 5). As shown in Table IV, statistical significance only exists in Type 3. We found that the participants could retrieve their memories in phonology but need a period of time to build up such memories. Learners, especially young children, need consistent support to build their literacy [77]. In the following, we report each type's participants' learning performance.

1) Radicals and Components (Type 1): Type 1 reflects the dimension of literacy. The average time spent was statistically significant, $p < 0.001$. Also, the average scores were statistically significant, $p < 0.005$. The average time spent was reduced by 31.949%, from 51.065 s in the 1st month to 34.750 s in the 6th month. The average score increased by 10.218%, from 0.875 in the 1st month to 0.964 in the 6th month. Thus, performance improvement in literacy was observed.

2) Orthographic Awareness (Type 2): There was a trivial improvement in Type 2 with respect to both average time spent and average score, but with no statistical significance. The time spent reduced by 18.505%, from 52.218 s in the 1st month to 42.556 s in the 6th month, $p = 0.196$. The average score increased by 10.251%, from 0.847 in the 1st month to 0.933 in the 6th month.

3) Phonological Awareness (Type 3): Statistical significance exists only in the average scores, $p < 0.05$, but not in the average time spent, $p = 0.282$. The time spent increased by 14.195%, from 63.378 s in the 1st month to 72.375 s in the 6th month. The average score increased by 24.263%, from 0.744 in the 1st month to 0.925 in the 6th month. Thus, performance improvement in phonology was observed.

4) Morphological Awareness (Type 4): No statistical significance was found in the average score, $p = 0.315$, and average time spent, $p = 0.837$. The time spent slightly increased by 4.439%, from 53.756 s in the 1st month to 56.143 s in the 6th month. Also, the average score increased by 12.274%, from 0.806 in the 1st month to 0.904 in the 6th month.

5) Speaking (Type 5): Type 5 consists of two games: 1) vocabulary quick naming games and 2) sentence-reading games. In the quick naming game, 54.11% of the participants got 1 point while 45.89% got 0 points. In the sentence-reading game, 43.38% and 19.40% of the participants got 3 and 2 points, respectively. The rest of the 37.31% participants got 0 points.

6) Writing (Type 6): The participants improved their writing score by 10.824% from 8.850 (σ=4.449) in the 1st month to 9.808 (σ=2.831) in the 6th month. The average time spent decreased by 17.94% between the 1st month ($\bar{M}$=16.408 s, σ=12.324) and the 6th month ($\bar{M}$=10.133 s, σ=5.124).

Fig. 9 illustrates the score and time spent on Radicals and Components (Type 1), Orthographic Awareness (Type 2), Phonological Awareness (Type 3), and Morphological Awareness (Type 4) with respect to the number of months. In general, students' score increased while time spent decreased over six-month training for four game types. Fig. 10 evaluates the overall writing performance. Students' score became less diverse after six-month training. Even students did not practice in the 5th month, and the median score was the same as that of the 1st month. Also, Fig. 11 demonstrates the performance of writing time over half-year. Students' time consumption in answering a question kept decreasing. Students took less time to retrieve their

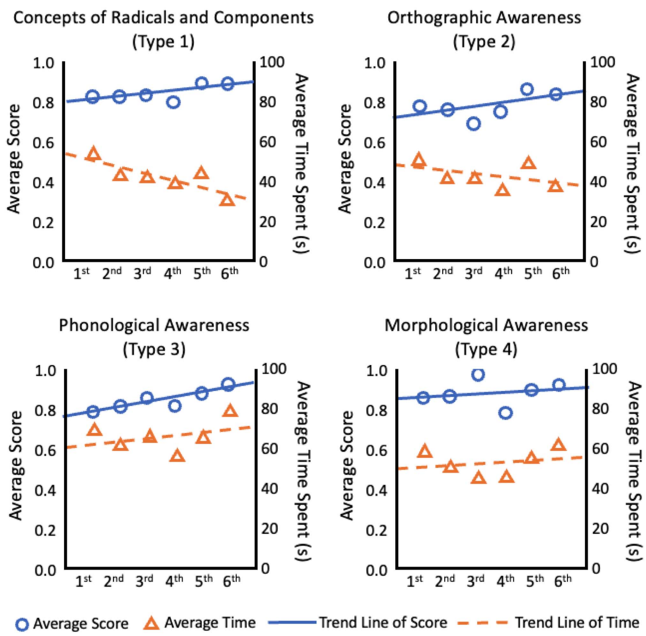

Fig. 9. Relationship between score and time spent in the games of Types 1–4.

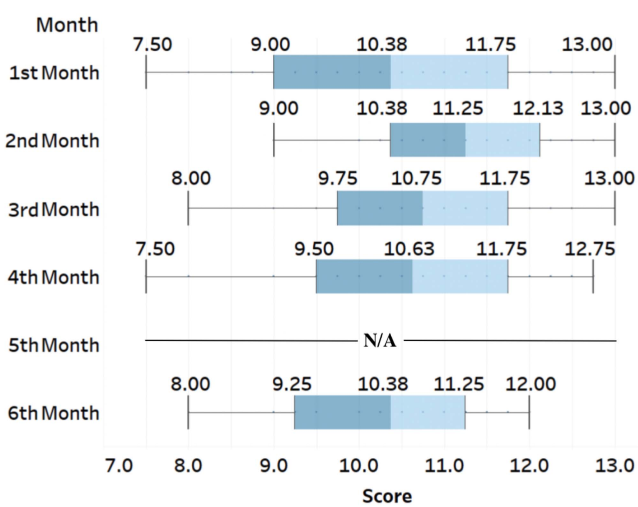

Fig. 10. Overall writing performance (The box-plot 50th is the median).

memory. Fig. 12 illustrates the relationship between score and time spent in writing games. Students spent less time but getting a higher score over the half-year training. The results prove that the app can effectively improve students' learning performance.

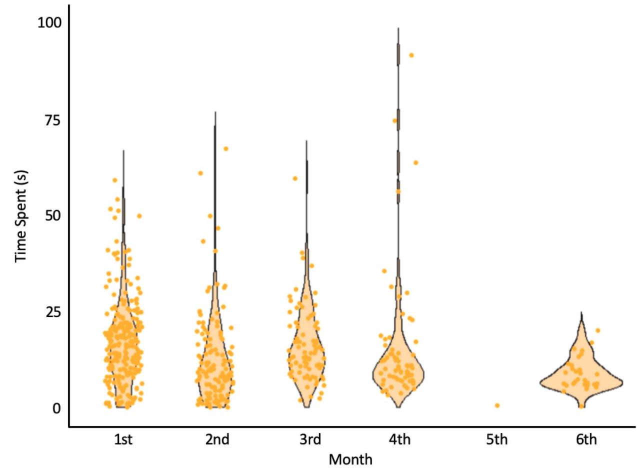

Fig. 11. Performance of writing time over half-year.

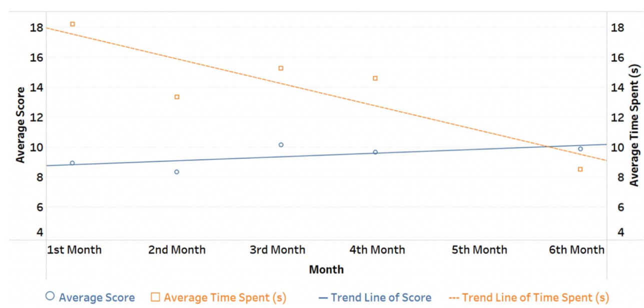

Fig. 12. Relationship between score and time spent on writing games.

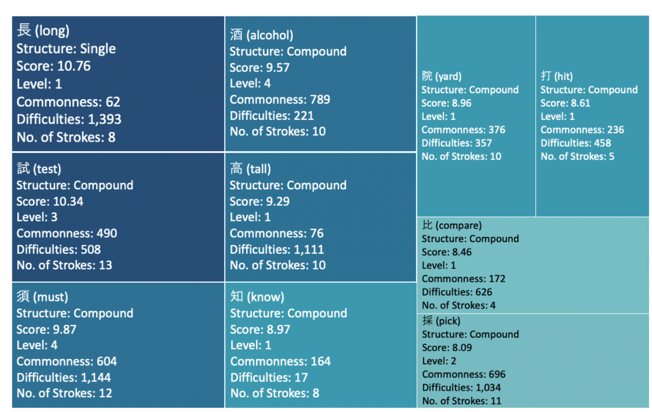

Fig. 13. Ten selected traditional Chinese characters, where the size and color of each rectangle indicate the count and score (the darker the higher), respectively.

B. In-Depth Analysis of Writing Tasks (Type 6)

Besides the scores and time spent, we scrutinized the traditional Chinese characters based on their characteristics, including difficulties, commonness, and the number of strokes. Fig. 13 indicates students' writing performance, in terms of character writing, in which the Chinese character with the best performance was "長" while the worst was "採". It is worth mentioning that "長" is a single structure character while "採" is a compounded character. "長" belongs to difficulty level 1 while "採" is in difficulty level 2. Also, "長" is more common than "採" in which "長" appeared as a radical in numerous compounded characters. Furthermore, "採" is more complicated than "長." Fig. 13 lists the 10 traditional Chinese characters introduced in Section IV-B and illustrates the critical factors such as difficulties, commonness, and the number of strokes. These factors may affect the participants' ability to write the corresponding characters.

TABLE V
SINGLE-FACTOR ANOVA FOR 13 COMMON MISTAKES

Common Mistakes		Sum of Squares	df	Month	M	σ	Mean Square	F	Sig.
Label 1. Non-characters*	Between Groups	0.81	1	December	0.750	0.866	0.81	4.9	0.0284
	Within Groups	24.37	148	May	0.933	0.966	0.16		
	Total	25.17	149						
Label 2. Directionality*	Between Groups	0.88	1	December	0.742	0.193	0.88	5.25	0.0234
	Within Groups	24.86	148	May	0.933	0.064	0.17		
	Total	25.74	149						
Label 3. Transposition*	Between Groups	0.81	1	December	0.750	0.189	0.81	4.9	0.0284
	Within Groups	24.37	148	May	0.933	0.064	0.16		
	Total	25.17	149						
Label 4. Stroke Insertion/Deletion*	Between Groups	0.67	1	December	0.742	0.189	0.67	4.02	0.0468
	Within Groups	24.55	148	May	0.908	0.071	0.17		
	Total	25.22	149						
Label 5. Disproportionate Spacing within or among Components	Between Groups	0.03	1	December	0.471	0.224	0.03	0.15	0.6957
	Within Groups	32.51	148	May	0.433	0.202	0.22		
	Total	32.55	149						
Label 6. Disproportionate Size within or among Components	Between Groups	0.51	1	December	0.496	0.208	0.51	2.53	0.1136
	Within Groups	29.82	148	May	0.350	0.175	0.2		
	Total	30.33	149						
Label 7. Broken Stroke Errors*	Between Groups	0.88	1	December	0.742	0.193	0.88	5.25	0.0234
	Within Groups	24.86	148	May	0.933	0.064	0.17		
	Total	25.74	149						
Label 8. Crossing Stroke Errors	Between Groups	0.11	1	December	0.700	0.212	0.11	0.52	0.4735
	Within Groups	30.57	148	May	0.767	0.185	0.21		
	Total	30.67	149						
Label 9. Incorrect Stroke Type*	Between Groups	0.74	1	December	0.725	0.201	0.74	4.09	0.0451
	Within Groups	26.63	148	May	0.900	0.093	0.18		
	Total	27.36	149						
Label 10. Strokes Clarity	Between Groups	0.1	1	December	0.281	0.133	0.1	0.81	0.3695
	Within Groups	18.29	148	May	0.217	0.085	0.12		
	Total	18.39	149						
Label 11. Bend Angle of Strokes	Between Groups	0.14	1	December	0.592	0.244	0.14	0.56	0.4553
	Within Groups	35.66	148	May	0.667	0.230	0.24		
	Total	35.79	149						
Label 12. Omission of Radicals/ Addition of Components	Between Groups	0.54	1	December	0.750	0.189	0.54	3.17	0.0770
	Within Groups	25.2	148	May	0.900	0.093	0.17		
	Total	25.74	149						
Label 13. Component Replacement*	Between Groups	0.88	1	December	0.742	0.193	0.88	5.25	0.0234
	Within Groups	24.86	148	May	0.933	0.064	0.17		
	Total	25.74	149						

Seven of them showed significance in the 6-month trials, which are denoted with (*).

Finally, we reviewed the overall writing performance marked by 13 labels (see Fig. 7), corresponding to common writing mistakes. Table V presents the statistical analysis of the 13 common writing mistakes, denoted as Labels 1–13. Significant main effects have been found in 7 out of the 13 labels. We list the labels with consequential effects between the 1st month and the 6th month, i.e., $p < 0.05$, as follows—-Label 1: Noncharacters (1st: 0.750, 6th: 0.933); Label 2: Directionality (1st: 0.742, 6th: 0.933); Label 3: Transposition (1st: 0.750, 6th: 0.933); Label 4: Stroke Insertion/Deletion (1st: 0.741, 6th: 0.908); Label 7: Broken Stroke Errors (1st: 0.742, 6th: 0.933); Label 9: Incorrect Stroke Type (1st: 0.725, 6th: 0.900); and Label 13: Component Replacement (1st: 0.742, 6th: 0.933).

C. User Retention Rates Among Six Game Types

We collected 3245 data in six months. Fig. 14 depicts 2372 valid quiz data. The participants demonstrated a low retention rate in general, with the following compositions (total quiz number, 1st-month quiz number, 6th-month quiz number): Type 1: Radicals and Components (777, 465, 28); Type 2: Orthographic Awareness (292, 174, 9); Type 3: Phonological Awareness (318, 193, 8); Type 4: Morphological Awareness (264, 156, 7); Type 5: Speaking (314, 146, 15); Type 6: Writing (407, 120, 30).

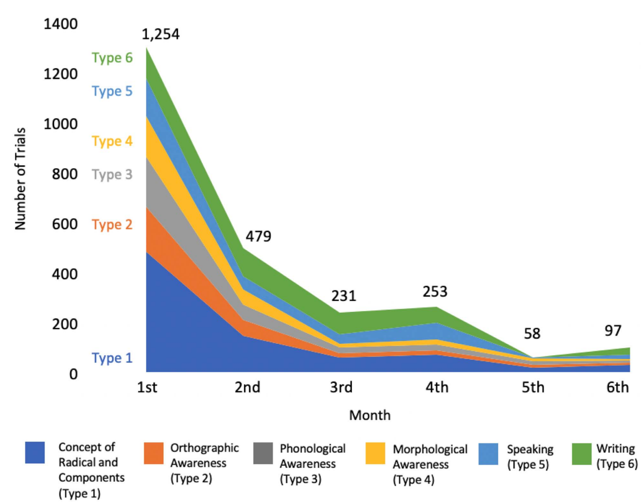

Fig. 14. Activeness of six-game types over six-month trials.

Throughout the six months, the participants preferred two game types, i.e., Radicals and Components (Type 1) and Speaking (Type 5). Furthermore, Orthographic Awareness (Type 2), Speaking (Type 5), and Writing (Type 6) were popular among the participants in the 1st month. In contrast, Radicals and

Components (Type 1), Speaking (Type 5), and Writing (Type 6) became more popular among the participants in the 6th month.

VI. Discussion

This work is the first effort to systematically study traditional Chinese learning by underprivileged students in the wild. In the following, we discuss learning motivation, children's learning engagement, and the constraints of mobile learning by underprivileged students.

A. Learning Motivation

According to Seligman's theory [78], [79], a sense of control motivates one to work hard and achieve. Setting goals not only allows learners to understand how the learning app could help them but also assists them in establishing positive expectations and confidence [80].

By sustaining a sense of achievement, learner satisfaction can effectively drive the learner's motivation. Providing intrinsic enjoyment may motivate students, even without external rewards [80], [81]. Game-based learning apps could provide intrinsic motivation for learning due to their crucial connection with goal-based learning [82]. VR technology could also establish intrinsic enjoyment due to its immersiveness compared to conventional learning methods [83], [84]. In particular, early-age learners can search for such intrinsic rewards by incrementally building their skills and knowledge in immersive environments, e.g., cardboard VR headsets. On the other hand, extrinsic rewards are also essential in triggering positive reinforcement to learners [80], even though intrinsic motivation may be more effective in motivating learners. A common strategy is giving learners conditional rewards, such as points, which may act as stimuli, to enhance their satisfaction [81]. Thus, intrinsic and extrinsic enjoyments are important motivators that deliver satisfaction to learners. This design has different game designs to motivate students to keep using the app. Also, we have added different sound effects and animations to make it more interesting for the learners.

B. Children's Learning Engagement

It was observed from the experiments that the underprivileged children enjoyed the game but used it less frequently than expected (i.e., retention rate). This finding supports Kucirkova et al. [85], where similar behaviors were observed for using educational apps and CD-ROMs at home. They found that, despite initial enthusiasm, children's time using the software declined quickly after the first week. Considering the design principles of Malone [86], we noticed some areas for improvement in the goal-setting and reward system of the game in this study [87].

First, we currently use a simple numeric format for goal setting to indicate the progress (see Fig. 15, 1.1). Also, this work does not include features that encourage collaboration between the child and their peers, teachers, or parents. Lack of collaboration and involvement in the learning process may be one of the critical factors leading to the low retention rate [88]. It was observed that students prefer the games of Speaking (Type 5) and Writing (Type 6). This phenomenon can be explained by the theory of structure-dependent engagement [89]. Children can interact more with the app, featured with the flexibility of creating their content, such as writing Chinese characters, reading aloud, coloring, and drawing apps [85]. Prior studies [90] found that they are more eager to participate in collaborative engagement activities because children are enthusiastic about the joint creation of individual elements, joint problem-solving, and thinking aloud [91], [92].

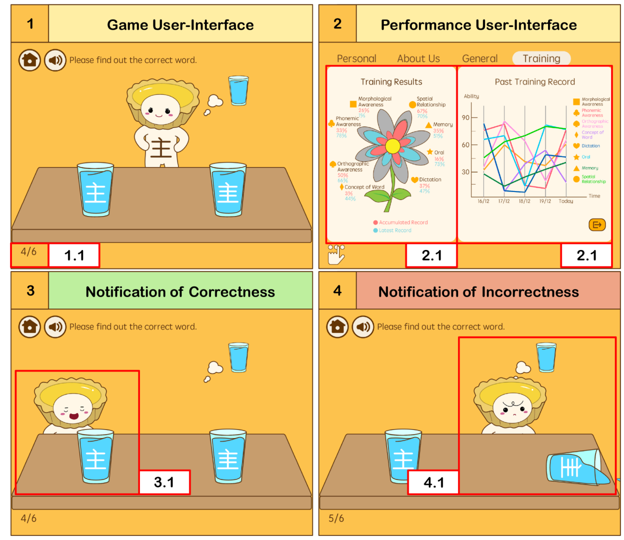

Fig. 15. Overview of the game setting.

Second, for the reward system, we are now using animation and sound effects to praise the children (see Fig. 15, 3.1 and 4.1). However, this may not be enough because the reward system was unidirectional. We could set some long-term goals, such as leaderboards with points and badges as milestones of the learning process [93], [94], [95], [96].

Third, the current game only provides simple feedback to the children, and experiments showed that more than simple feedback is needed to help students' skill development. Thus, we suggest immediate automated feedback combined with explanatory strategies, which can trigger positive perceptions in engagement [97], [98].

C. Constraints of Mobile Learning by Underprivileged Students

Long-term school closures caused a more harmful impact on students from low-income families [99]. Digital insufficiency widens the learning gap between rich and poor students [100]. In this study, the participants were recruited from underprivileged groups. Almost all students do not have a quiet and fixed place for after-lesson studying (see Section VI-D1). The participants cannot concentrate on learning in such noisy environments. Even worse, some students need a dedicated location for studying [9]. When we analyzed the speaking data, we discovered that almost all children were learning in a noisy environment full of noise from television, broadcasting, music, and noise from their neighbors' kids. During the six months of remote learning, the participants only made small improvements, and the limited study environments may be the main reason for this.

D. Limitations

In this section, we summarize some limitations of this research.

1) Data Quality: We analyzed the games of Type 5, in which noisy environments affect data quality and retrieval. Six conditions, which are adversaries to our analysis, have been identified.

1) A remarkable amount of audio (19.43%) demonstrates that participants read the vocabulary while some people were talking nearby or the participants were watching the television or listening to music. So, we cannot retrieve the speaking content accurately.
2) A few participants (5.10%) stopped the recording earlier. As such, we could only collect such data partially.
3) Some audio records (4.14%) contained an adult voice, showing that the participants read aloud with adults.
4) Similarly, 3.18% of audio-only contains the voice clips of adult users.
5) We sporadically recorded the scenario in which two or three children read aloud a sentence together (2.23%). As the voices are inseparable, the data could not be used.
6) We received a small portion of audio tracks (1.27%) in which participants read the vocabulary correctly in their first trial. Nevertheless, some adults, possibly their parents and grandparents, made incorrect pronunciations in their second trials. Consequently, the participants followed incorrect advice and failed in their third trial.

2) Children Learning In-the-Wild: In this work, the participants were relatively young (i.e., grades 1–3), and they learned at home (i.e., in-the-wild), without guidance from parents and teachers. Therefore, we could not control how the participants learn with the app. As a result, no data were collected in the 5th month.

In the following, we highlight several measures to reduce the missing data in future studies. First, we can add one function to allow teachers or instructors to send participants reminders [101]. Second, we can provide participants with appropriate motivation schemes, such as a leaderboard promoting competition among peer learners [102], [103]. The achievement system is more attractive for children because they will climb the leaderboard by doing well in weekly engagement measures [104], [105].

3) Fair Assessment: The current analysis only compared students' performance before and after the 6-month training. It will be more convincing to compare students who participated in the experiment with those who did not, such as the 33 participants who did not use the app but could still learn Chinese in different ways, e.g., by reading books, watching TV, etc. However, due to the COVID pandemic, we failed to follow up with those 33 participants.

4) COVID-19 Pandemic: Even though this study was motivated by the COVID-19 pandemic, the number of participants was limited by the worsening COVID-19 situation, leading to fewer data being collected.

VII. Conclusion

This article serves as a groundwork to understand the potentials and limitations for early-age underprivileged learners to learn traditional Chinese by apps at home. It was observed that early-age learners could significantly improve in the fundamentals of literacy and phonology without direct supervision. Improvement was also found in more than half of the common mistakes in writing (7 out of 13). However, learners did not achieve significant improvements in the aspects that require continuous guidance and supervision.

Our study identified the limits of deploying mobile learning platforms, particularly for underprivileged learners. The systematic framework revealed the insufficiency of traditional Chinese learning on mobile apps and shed light on the design opportunities. In the future, we plan to re-iterate the app in the aspects where students could not achieve significant improvements. This attempt could make learning in-the-wild more viable and effective. We will also reinforce the gamified elements to improve user retention. In addition, we will deploy the modified app on a larger scale and include subjects from the high-income group to gain a deeper understanding of the impact of digital learning on the learning gaps. Finally, we will apply the framework to other languages to benefit a larger community.

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