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Approaching Chinese Radical Awareness through 3D Printing (用 3D 打印培养汉字偏旁意识)

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Abstract: Radical awareness has proven beneficial for Chinese character learning. Although radical knowledge is typically introduced at the early stages of L2 Chinese learning, its application is often delayed. This exploratory case study explored an innovative technology-mediated task design to introduce 3D printing to character teaching. The 3D printed characters physically reshaped the learning unit from stroke to component and introduced haptic learning. Upon completion of the 3D character project, the learner exhibited improved recognition of form and meaning for radicals, characters, and the interactions thereof. The learner was better able to notice the size, meaning, form variation of radicals, and the in-depth configuration and compositional logic of components, as well as to restructure character network via radicals. Additionally, by viewing the task as an interactional blueprint to engage teacher-student collaboration, this study iteratively developed a 3D character task series comprised of 3D character composing, radical knowledge instruction, character network building, and handwriting practice.

摘要：培养汉字偏旁意识有助于学习汉字。汉语二语学习者往往在学习初期就接触到偏旁部首，却无法及时掌握并应用。本文通过探索性个案研究将 3D 打印引入汉字教学，发现 3D 汉字帮助学习者实现了汉字学习单位由笔画到偏旁部首的转变。学习者通过完成一系列 3D 汉字任务提高了应用偏旁部首知识的能力，加深了对偏旁的大小、意义、形状变化、汉字结构及构字法的认知，并能通过偏旁将汉字进行关联、重组。另外，本文通过开放性的任务设计由师生共同参与、摸索出了一套由 3D 汉字重组、偏旁教学、汉字网络建构、汉字手写构成的组合任务。

Keywords: Chinese character learning, radical awareness, 3D printing, task as an interactive blueprint

关键词: 汉字学习、偏旁部首意识、3D 打印、动态任务设计

1. Introduction

Chinese characters have been a major challenge for English-speaking Mandarin learners (Everson, 2011; Ke, Wen, & Kotenbeutel, 2001). With a nonalphabetic orthography, Chinese dictionaries sort characters by selective character components called radicals (部首, *bùshǒu*), meaning "section head". Radical awareness relates to understanding the role of radicals in the Chinese writing system (Li, Anderson, Nagy, & Zhang, 2002). Shen and Ke (2007) defined radical awareness as the functional understanding of the role of radicals in forming Chinese characters and the ability to use this knowledge consciously in learning characters.

Radical awareness is a crucial part of Chinese morphological knowledge, and it has proven beneficial for L2 Chinese character learning (Chen, Allport, & Marshall, 1996; Taft & Zhu, 1994; Taft, Zhu, & Peng, 1999). L2 Chinese teaching has undertaken varied approaches to facilitate radical awareness, including technology-assisted means of instruction. Three-dimensional (3D) printing provides new opportunities for character-learning task design via elevated visual and haptic sense of form and space that are infeasible in 2D representation. There have been attempts introducing 3D printing technology into a language classroom by reporting on the design of different spatial character models (Kanev, Oido, Yoshioka, & Mirenkov, 2012). The application of 3D printing in character learning, however, lacks a systematic pedagogical design. One challenge is that designing technology-mediated tasks requires navigating a more complex set of issues compared with designing face-to-face tasks (Lai & Li, 2011). Moreover, no study has monitored and evaluated the effects of 3D printing technology on character learning.

This case study explores an effective task design for incorporating 3D printing technology into L2 Chinese learning and investigates how it might affect radical awareness development. The exploratory process also provides an example for innovative technology-mediated task designs by navigating a teacher-student collaborative framework with applicable steps.

2. Review of literature

2.1 Instructions on Radical Awareness

Radical awareness, despite its early benefit for L2 Chinese character learning, plateaus from the end of first year through the end of second Chinese character learning (Shen & Ke, 2007). Attempting to address the plateau, a few recent studies explored radical awareness instruction in lower-level Chinese classrooms of English speakers, and reported positive results from facilitating learners' identification and establishment of an association between radical and character. Shen and Xu (2015) directed elementary-level learners to use orthographic knowledge to associate radicals with the sound, shape, and meaning of characters. Such association-making effort was reported to have promoted mental processing of characters and helped develop a character network. Xie (2019) designed open-book radical assignments for elementary-level learners that provided character formulation information, showed English definitions and/or sounds of radicals/units, and required identification and writing of the appropriate radicals/units. Learners reported improved radical knowledge and application in character processing, but no change in overall character learning strategy. Xu and Padilla (2013) found incorporating meaningful interpretation and chunking (MIC) of character enhanced immediate learning and retention for high school students at elementary to intermediate level. They also found allowing students the agency of creating MIC themselves more effective than imposing teachers' interpretation and chunking.

In addition to identifying and establishing the radical-character association, this study argues that character learners need a pedagogical design where they can proactively apply radical-character association in reproducing characters. It is noted that productive character practice imposes challenging cognitive restructuring onto the learners as they go through four steps: *task identification*, *task representation*, *decision making*, and *decision execution* (Shen & Ke, 2007). In the case of a character composing task, learners must first *identify* that the task is for them to sort out the correct combinations of components and use them to compose characters. Learners' second step is resorting to long-term memory about radical meaning, form, and compositional relations, as well as character configuration and orientation. During this phase, learners must mentally *represent* the task and hypothesize different combinations that may emerge simultaneously. This is a highly complex cognitive process. Third, learners must *decide* which combinations are appropriate, after potentially resuming and evaluating many combinations in mental representations. Finally, learners *execute* the decision by writing or dragging together online the compound characters. The cognitive restructuring process in a character composing task reveals that the radical-character association is far more complex than a point-to-point connection. It exhibits an intricate network coordinating information of radical meaning, form, and compositional relations, as well as character configuration and orientation.

2.2 3D Printing Tasks for Chinese Character Learning

Affordance of 3D printing technology does not merely transfer a task into a 3D setting, rather, it shapes and adds possibilities to the task design and practice. To continue with the character composing task, it is not exactly executable to combine mixed components when handwriting characters stroke by stroke. A computer screen may allow learners to digitally drag character components together, but is still faced with technical challenges. One challenge is the unavailability of non-radical components in computer input system. Another challenge is that even for radicals that are accessible via typing, they are not necessarily stored in their original form being part of a compound character. For instance, the typable 女 takes its form as an independent character rather than its narrow or compressed form being a radical in characters like 妈, 娄. Similarly, the typable 贝 does not take its radical form in characters like 购, 贡, or 赢. Such challenges faced in a 2D mode can be addressed by 3D printing technology. Additionally, printing the characters and manually cutting the paper to separate character components can leave clues to the orientation. In contrast, 3D printed characters are individually complete yet remain dissectible into true-sized components.

In addition to enabling full execution of the character composing task, 3D printing technology presents learners with additional haptic cues. Haptic information helps learners draw upon tacit embodied knowledge through bodily experiences (Reiner, 1999, 2008). Haptic technology provides users with somatosensory (touch) information by simulating an object's hardness, weight, or inertia, as well as its shape, smoothness, slippage, and temperature (Bivall, Ainsworth, & Tibell, 2011). Meaning-making is a dynamic process that involves visual, aural, and kinesthetic representations. Rather than simply add together information received from different sensory channels, multiple modalities coordinate to confirm, complement, and even challenge each other to provide comprehensive resources for further contemplation and analysis (Kress & van Leeuwen, 2001). The use of multimedia tools and animations have provided important support for character recognition, stroke orders and sequences learning, as well as associations building between phonetic, semantic, and orthographic components of Chinese characters (Chen et al., 2013; Chung, 2008; Jin, 2003; Zhan & Cheng, 2014). Moreover, multimedia instruction also demonstrated positive effects when applied in combination with writing and/or reading (Xu et al., 2013; Xu & Padilla, 2013). Character learning has attempted to integrate haptic information by typing with finger(s) following the pre-recorded letter/character trajectory on touchscreen (Eid et al., 2007). The application of finger touch and stroke-tracing, however, could be considered narrow haptic sensory because only the fingertips are engaged. 3D printing technology enables an integration of in-depth haptic sense via full hand touch of 3D objects. 3D printing technology not only enables full execution of a character composing task, but also adds more variations to the task design.

2.3 Task as an Interactional Blueprint

An effective task requires deliberate design and engaging implementation. Thorne (2005) defined tasks through two stages: task-as-workplan versus task-in-process. Before walking into the classroom, instructors have a task design in mind as the workplan. Once in process, learners superimpose their own various learning purposes on the given task-as-workplan and reinterpret it as they adjust their actual task-in-process between achievement and survival purposes (Breen, 1987). Because it is the actual conduct of the task that generates diverse learning outcomes, task quality and efficacy should be evaluated by how it actually unfolds. Rather than analyzing the structure of the task, research should focus on the task-in-process and examine the derived features from the interactional demands it placed on participants (Samuda & Rounds, 1993). To reconcile the dynamic interaction between task-as-workplan versus task-in-process, Jenks (2006) defined task as an interactional blueprint that establishes a framework for guiding task-takers to successful completion with flexibility of interpretation and negotiation. By this definition, the task-taker and task-designer have equally important perspectives. Researchers should be more cognizant of how learners perceive the goals, procedures, and significance of tasks (Duff, 1993).

This study fully recognizes the dynamic interaction between task-as-workplan and task-in-process. Viewing task as an interactional blueprint, this study took a teacher-student collaborative approach at designing a 3D character project. The instructor elicited learner's input throughout the project to understand how the learner actually executed the task and revise the designs for future learning.

3. Research Questions

This study explores two primary research questions:

1. How does 3D printing technology affect early L2 radical awareness development?
2. What may be an effective task design applying 3D character learning in an elementary-level Chinese class?

4. Methods

4.1 Exploratory Case Study

When there are no earlier studies on a particular topic, exploratory research can set the foundation for future conclusive research (Bhattacherjee, 2012; Singh, 2007). An exploratory case study offers an in-depth analysis of the complex real-life changes and interrelations of different contextual factors (Gillham, 2000; Yin, 2014). This study employs an exploratory case study approach for three main reasons. First, given the scarcity of studies on applying 3D printing technology in Chinese character learning, there are many unknown dynamics that a controlled method may not be able to elicit. Second, a case study in a one-on-one teaching setting allows focused observation and elicitation of learner's behavior and perspective. Finally, the accessibility and affordability of 3D printing equipment, material, and training is still limited. An exploratory case study investigating the applicability and effectiveness of 3D character tasks can shed light on wider classroom adoption of 3D characters.

4.2 Participant and Research Context

Participant Chris (pseudonym) is a junior staff member (Age: 35) at a private research university in the U.S. Growing up as a third-culture kid, he has lived across the world and had studied Afrikaans, Spanish, and Italian (for 0.5-2 years each). Seeing an increased population of Chinese international students on campus, Chris aspired to better serve their wellbeing and received university support to study Mandarin. His goal was to be able to have simple conversations in Mandarin with Chinese students, and gain further understanding of their experiences, culture, and perspectives. After completing 22 hours of one-on-one study sessions with the instructor (who is also the researcher), Chris took a two-week work trip to Shanghai. During this trip, he received intensive exposure to Chinese characters on street and store signs, public transportation maps, as well as inside buildings. The intensive input motivated him to have a better grasp of Chinese characters. Therefore, the instructor designed a character project utilizing 3D printing technology for

Chris. Prior to the 3D character project, Chris had been continuously taking individual sessions with the instructor for a total of 39 hours across three months.

The instructor and Chris completed a 3D printing workshop with safety training. The university offers a makerspace that provides students hands-on experiences beyond traditional classrooms, aiming to foster students' creativity, ingenuity, problem solving, and intellectual curiosity. The makerspace provides free access to Ultimaker (3 and S5) 3D printers, as well as printing materials including polylactic acid (PLA) and polyvinyl alcohol (PVA). Prior to the use of the 3D printers, the makerspace staff offer users safety training and workshops on Tinkercad design software and Ultimaker Cura slicing software. The staff are also available for technical support and troubleshooting consultation throughout the process of 3D printing.

4.3 Objectives and Procedures

One week prior to the 3D character project, the instructor interviewed Chris to establish the learning objectives and procedures. In the interview, Chris shared that his biggest challenge of character learning was the stark difference between two writing systems. He had been relying on rote memorization for character learning. However, he occasionally found it helpful to connect new characters with previously learned ones that share components. Once he identified shared parts, he could then decompose characters to focus on the unknown parts. By doing so, he leveraged his existing knowledge rather than re-learning the whole character. However, he self-critiqued for making up his own compositional reasoning and desired a systemic orthographic understanding.

The instructor and learner then established learning objectives. Upon completion of the 3D character project, Chris would be able to: i) gain knowledge on basic radicals; and ii) apply radical knowledge in character processing. To reach the objectives, five 1.5-hour weekly sessions were designed, each consisting of three steps. Step One was a 3D character composing task designed in accordance with learners' four cognitive restructuring phases. The characters (see Appendix A) were selected according to two principles: 1) the characters included varied structures: integral, left- (middle-) right, top- (middle-) bottom, or (Half-) enclosure; and 2) the characters are composed of targeted radicals studied in the textbook of use: *Integrated Chinese Vol. 1* (4th ed.) (Liu, 2016). Before the session started, the instructor mixed up and laid out the 3D components of eight characters. To begin with, Chris *identified* his task to sort out the correct combinations in order to compose eight characters. He then referred to radical and character knowledge as he tested out different *representations* of 3D component combinations. Based on evaluation of such externalized representations, Chris finalized the *decision* on his pick of combinations and *executed* his decision by reproducing eight characters, either correct or mistaken. Step Two was a radical knowledge instruction session. The instructor asked scaffolding questions to heuristically guide Chris to identify the sound, shape, and meaning of radicals as well as their role in compound characters. Step Three aimed to create a character network via shared radicals. Chris was asked to brainstorm other characters sharing the same radicals and compare their meanings, and then explore online dictionaries for characters listed under the designated radical. As the task design evolved with learner's continuous feedback, Step Three later eliminated the brainstorming, but proceeded with online dictionary exploration and additional review of previously learned characters sharing the same radicals.

4.4 Data Collection and Analysis

A mixture of qualitative and quantitative data was collected to measure progressive radical awareness development. At the end of each study session the instructor interviewed Chris for 15 minutes to elicit his self-perceived performance, strategy, and feedback. The interview results were used to track his performance and co-construct the task design for future sessions. In addition, Chris received pre-test (See Appendix B) and post-test (See Appendix C) to assess his radical awareness change. Table 1 summarizes the timeline of data collection.

Table 1 Timeline of Data Collection

Prior Week	Week 1	Week 2	Week 3	Week 4	Week 5
Pre-test	Study Session 1	Study Session 2	Study Session 3	Study Session 4	Study Session 5; *Post-test*
Interview A	Interview 1	Interview 2	Interview 3	Interview 4	Interview 5

4.4.1 Semi-Structured Interviews

In addition to Interview A (see Table 1) that established the learning objectives, weekly semi-structured interviews were conducted to elicit the learner's perceived task-in-process and facilitate teacher-student collaboration on task design. Each interview started with Chris self-assessing and reflecting on his in-session learning experience and comparing his character learning process in 3D versus 2D. Chris was then probed on his thinking process during specific in-session performance. Next, Chris was asked to provide suggestions on the instructional design of upcoming study sessions and potential applications of 3D character learning in a classroom setting. Finally, each interview concluded with an open-ended question for Chris to share additional feedback. All interviews were audio-recorded. The recordings were transcribed by Amazon Transcribe and then proofed by the researcher.

4.4.2 Radical Awareness Test

In addition to the weekly interviews, pre- and post-tests were conducted to examine Chris's radical awareness development. The format of pre- and post-tests was adapted from He and Ke's (2007) but replaced the vocabulary test with a character writing test. Both tests consisted of four sections. The first section *radical perception test* asked to identify the character structure with provided options (i.e., left- (middle-) right, top- (middle-) bottom, (half-) enclosure, integral) and then decompose the character components. The second section *radical knowledge test* asked to provide the English meaning of the given radicals. The third section *radical knowledge application test* consisted of two parts. Part A provided groups of three novel characters sharing an identical component but different radicals. It asked to judge the meaning of radicals and select the character that best fits the English translation provided. Part B provided partial characters and asked to write out the missing radicals based on the English meaning of characters. This part was considered challenging because it required both writing the correct radical and adding it in correct position (e.g., left, right, top, bottom, enclosure) based on knowledge of character configuration, orientation, and composition. To avoid giving out configurational information, every given part of characters took a full character block (e.g., 半, 龙) rather than a partial character block (e.g., 半, 龙). The last section *character writing test* required writing characters with pinyin and English meaning provided. To assure consistent item distribution and difficulty, the pre- and post-tests were evenly split from a master test, except that both second sections shared identical items. When completing the third and fourth section, the learner was not allowed to refer to the first and second sections.

5. Results

The results showed that application of 3D printing technology facilitated the early radical awareness development of the L2 Chinese learner. The collaborative and iterative effort between teacher and student led to a successfully designed 3D character learning task series. The subsequent sections provide an in-depth look at the results.

5.1 Radical Awareness Development

The end-of-session interviews revealed progressive development of the learner's radical awareness along the five weeks. Throughout the project, Chris repeatedly expressed his excitement and affirmed his belief in its faciliatory effect on character learning. Upon completion of the 3D character project, Chris commended (in Interview 5) the project was "a huge success" and believed that he mostly achieved the goal by "having a better understanding of what radicals are, how they impact meanings of characters, and how they combine to make characters". Chris's performance and feedback fell into several different categories: character processing units, character configuration, compositional relations of character components, and character network building via radicals.

5.1.1 Radical as a Processing Unit

By holding 3D radicals in hand, a learner may conveniently perceive them as units of form-meaning connections. For instance, holding a 3D radical 女 (female) as a whole, Chris claimed (in Interview 1 and 4) it helped him perceive it as an individual meaningful unit rather than three inextricable strokes, which naturally directed his attention to the assembling logic of these 3D pieces.

Such processing unit shift from stroke to radical was confirmed in another example. When trying to put together 大 (big) and 耳 (ear) for character 耷 (big ear), Chris rotated the 3D piece of 耳 clockwise to figure out its orientation. As he reflected (in Interview 3), it was due to his unfamiliarity with component 耳 and its spatial relationship with 大. By contrast, he would not need to rotate 大, he claimed, because 大 is so common that he quickly identified and established its form-meaning connection. With the strokes not dissectible in 3D pieces, Chris was forced to process at radical level. It is also worth noting that component rotating is not possible in a handwriting mode but is enabled by the 3D presentation. This extra possibility helped Chris notice an additional dimension of character component layout: orientation.

With radicals established as individual meaningful units, Chris's attention was further directed to its variations. Chris noticed one radical may take variations in shape and position. Continuing the example of radical 女, Chris commented (in Interview 4) that 女 may be tall and thin, taking the left side of a character such as 女 in 姐 or 娜; Alternatively, 女 may be short and wide, taking the bottom position such as 女 in 要 or 姜 (See Figure 1). Processing at radical level amplified the shape variation of the same radical, which was more noticeable by the learner. In addition, being able to hold tangible 3D radicals enabled the additional haptic sensory for noticing the difference.

Figure 1 Pictures of 3D Printed Characters: 女、姐、娜、要

5.1.2 Character Configuration

The 3D pieces allowed the learner to gauge the size of character components using both visual and haptic senses. Since Chinese characters all fit into a standard square, a learner must identify, measure, and copy the character size and structure, which is challenging in handwriting. Therefore, character handwriting practice sheets typically print blocks for learners to write within the lines. According to Chris (in Interview 3), the additional height of a 3D character delineates an invisible outline square that is tactile compared with a 2D block. Learners may judge whether two pieces belong together by measuring how well they spatially (i.e., horizontally, vertically, enclosed) fit together to form a standard square. For instance, a component of a left-right configured character (e.g., 扌) would not spatially match a component of a top-bottom configured character (e.g., 癶). Chris's sense of a standard square was even fine-tuned to differentiate characters of the same configuration. For instance, after trying out different combinations of 𧾷, 亡, 忄, and 包, he finally decided and executed the correct combinations of 忙 and 跑. One of the reasons Chris (in Interview 4) rejected the combinations of 𧾷亡 and 怉, was that 𧾷亡 looked wider than a normal character.

In addition to the square size of a whole character, the learner's attention was further directed to nuanced balance between compositional parts. In his aforementioned rejection of the 𧾷亡 and 怉 combinations, he (in Interview 4) also observed that the stroke 一 of 亡 is high up next to the 口 of 𧾷, whereas the end of stroke ㇒ in 包 fits into the open space below the 口 of 𧾷. He therefore concluded that 𧾷 and 包 fit better, taking into account both the character square size and the within-character balance. Moreover, Chris also raised awareness of the balance between space and stroke numbers. He concluded (in Interview 4), though to be orthographically validated, that the left-side components usually have a small number of strokes if taking a small portion of the character space. Being able to test out different 3D radical combinations pivoted learner's discovery of the inner-character interactions in terms of component size, stroke shape, and stroke number.

5.1.3 Compositional Relations

The 3D character project facilitated Chris's coordination of both radical form and meaning cues, through the process of deducing the component compositional relations. Chris demonstrated coordination of form and meaning in positioning the individual components within a character. At earlier stages (in Study Session 2), Chris made mistakes by reversing the components, but despite that he was able to quickly identify the character configuration. For instance, Chris quickly identified 口 and 丩 in a left-right configuration based on their shape, but horizontally reversed the two pieces and created a noncharacter (丩口). As he learned more semantic radicals, he was more able to tap into radical form and meaning when figuring out their configurational position. For instance, Chris surmised (in Interview 2 and 3) that 宀 (roof) often goes on top based on its meaning, thin-shaped radicals such as 口 in 哪, 日 in 明 go on the left in accordance with their form, and 灬 (fire) always takes the bottom place based on its form and meaning. The mistakes Chris made also reflected the mental rulesets that he had created. After identifying 夕 and 口 in a top-and-bottom configuration, Chris created a noncharacter (口夕) by vertically reversing the two components. The reason, as Chris reflected, was that he had mistaken 口 for the roof radical 宀 on top. Chris asserted that he would have not made such mistakes, had he handwritten on a stroke basis instead of processing at a component level.

In addition to positioning individual radicals, Chris worked to rationalize the layout of components through meaningful interpretation of their compositional relation. After placing 木 and 子 in a top-and-bottom configuration, Chris created a noncharacter (子木) by vertically reversing the two components. His reflection (in Interview 3) revealed that he navigated the composition through both form and meaning cues. He thought having 木 at the bottom built a balanced foundation whereas having 子 at the bottom seemed stilting. Furthermore, trees are rooted in the ground. After the instructor explained that fruits hanging down the tree makes a character 李 (plum), he was excited by the meaningful composition of 木 and 子. This composition relation was uptaken as Chris was able to write the character 李 in its correct form in the post-test. Chris continuously looked for meaningful compositional relation to help memorize the characters, but was aware that many characters lack transparent and applicable orthographic reasoning due the changes over time. Following Xu and Padilla's (2013) suggestion to let students create their own interpretation rather than imposing teachers' interpretation and chunking, this 3D project encouraged Chris to create his own rationalizations even if not orthographically valid. For instance, Chris (in Interview 3) decomposed 都 (all) into 土 (earth), the 日 (sun), and 阝 (ear, mountain). He then interpreted 都 as everything between heaven and earth, and used this interpretation to rationalize the combination of these three components and solidify his memory of the character. Learning and applying radical knowledge in character compositional relation engaged Chris in higher-level cognitive effort, which enhanced the learner's character memorization. Chris (in Interview 5) believed such memories "would stick harder and come alive easier when needed", compared with the character memory gained through mechanically copying characters.

5.1.4 Character Network via Radicals

By exploring and reviewing characters sharing the same radicals, Chris was presented opportunities to proactively build a character network for efficient character learning. Chris expressed (in Interview 3) his appreciation for being able to explore online dictionary pages where unknown characters are listed by radical. Typically, students learn new characters along the introduction of new vocabulary. By participating in the 3D character project, Chris started restructuring his character repertoire by building a character network via radicals. Rather than incidentally accumulating characters alongside the introduction of new vocabulary, Chris systemically made connections among unrelated and even unknown characters. For instance, when exploring characters sharing radical 阝, Chris was surprised to realize that there are left-sided 阝 (mountain slope) shared by topographic features (e.g., 陵, 陡, 险), and right-sided 阝 (city, county) shared by many place names (e.g., 郦, 邛, 邗). He expressed appreciation (in Interview 3) for systemically making such connections and categorizations, helping in his effort to organize learned characters. Chris (in Interview 5) had primed himself to "always be on the lookout for specific radicals to grab on to when learning new characters", which indicated a development of radical awareness and readiness for its application. Chris reflected that such radical awareness prepared him with a great foundation and confidence for learning new characters in the classroom and beyond.

5.1.5 Overall Radical Awareness Development

Results of the pre-and post-tests confirmed the findings from weekly interviews on Chris's radical awareness progress, as shown in Table 2. In the first section, *Radical Perception*, Chris demonstrated a good sense of character configurations by achieving almost perfect scores. He lost points in both pre- and post-tests due to over-decomposing compound characters. For instance, rather than decomposing 图 (enclosure structure) into two meaningful components of 囗 and 冬, Chris over-decomposed 图 (enclosure structure) into 囗， 夂， and ⺀. Another example of over-decomposing was dissecting the phonetic component of 馆 (left-right structure) into 宀 and 㠯. All over-decomposing occurred with non-radicals, for which Chris had not yet established the form-meaning connections and perceived only visibly separate form. Since the 3D character project focused on radical components, improvement in non-radical components would not be expected.

In the second section, *Radical Knowledge*, Chris was able to identify and write down the specific meaning of 22/30 radicals in pre-test and 24/30 radicals in post-test. However, the reasons Chris lost points each time were different. In the pre-test Chris lost points mostly due to giving no answers or wrong answers, but in the post-test Chris lost points mostly due to giving only generic meaning of same semantic category radicals such as 走 (walk, run), ⻊ (foot), and 辶 (tread). It seemed that the 3D character project helped him identify the semantic categories of radicals.

The third section, *Radical Knowledge Application*, was considered the most challenging. However, Chris's scores improved by 8 points in this section from the pre-test to the post-test. This is the biggest improvement out of the four sections, with the most improvement found in the Part B of this section. Chris showed increased capability of identifying the missing semantic radicals and writing them out at the correct position (i.e., top, bottom, left, right, enclosed, inside).

In the final section, *Character Writing*, Chris was able to correctly write 22/30 characters in the pre-test and only improved by one in the post-test. One potential cause was that the 3D project focused on reproducing characters with provided components and did not require writing the characters. Even though there was not much improvement in Chris's score, he again lost points for different reasons in the pre- and post-tests. In the pre-test, Chris mainly lost points due to leaving blanks. In the post-test, Chris lost points due to confusing radicals (忙 written as 丬亡) or writing only the radical (病 with only 疒), which still showed his progressed character knowledge.

Table 2 Pre- and Post-tests Scores

	Radical Perception (20)	Radical Knowledge (30)	Radical Knowledge Application (30)	Character Writing (30)
Pre-test	18	22	19	22
Post-test	19	24	27	23

5.2 An Evolving Instructional Design

In addition to reflecting on his performance and strategy, Chris was also invited to share input on the instructional design in the weekly interviews. The instructor then interpreted the student's feedback in the framework of radical awareness operationalization, and further incorporated it within the established project objectives and procedures. By viewing the task as a teacher-student joint effort it became an interactional blueprint that shaped an evolving instructional design.

5.2.1 Task Series on Demand

Each study session began with a 3D character composing task which Chris found (in Interview 5) "a really different way of studying Chinese" and significantly sparked his curiosity, compared with relying on rote memorization. After Chris was spotted (in Study

Session 3) rotating radical clockwise for its correct orientation, the instructor deliberately displayed the radicals in random orientations. The purpose was to present an opportunity for the learner to raise awareness of radical orientation.

Once Chris sorted out eight characters with an identification of radical-character associations, the instructor (in Study Session 1) asked Chris to brainstorm other characters that share the same radicals to compare and contrast. Chris found this very challenging, which indicated that learner needed scaffolding to navigate a complex process of building character networks via radicals. The instructor therefore moved to the next task where Chris browsed an online dictionary for lists of characters that share the designated radicals. The instructor also eliminated the brainstorming task in the following sessions but focused on online exploration with scaffolding. In addition to scaffolding, the online dictionary exploration provided a positive affective filter for learner. When going through the dictionary sites, there occurred rare characters that even the instructor did not recognize. Chris commented (in Interview 3) that made him realize “even native speakers do not necessarily know all the characters”. This realization allowed him to feel less anxious and more encouraged to be exposed to and learn unknown characters. The online exploration also served as a springboard for sustained conversations on radicals and radical-character associations that typically hold no place in a structured classroom. For instance, when going over the characters sharing 女 (female) radical, the instructor shared how such characters, derogatory or commendatory, revealed Chinese traditional value and perception of women. Chris was exhilarated by such conversations and commented (in Interview 5), “I just feel like I have been on a track learning structured grammar and vocabulary following the textbook, whereas this project is so open and I got to ask these random questions and learn these pieces that I wouldn’t have been able to... I wouldn’t have thought to ask those questions just from reading the textbook.”

While Chris enjoyed the online dictionary exploration, its task design could become unfocused. For frequently used radicals there can be too many characters listed to fully review. The instructor’s response was more selectively exploring characters under each radical. The instructor then counterbalanced the scope of character network in online exploration by tasking Chris to scan the textbook vocabulary list for learned characters sharing the designated radicals. Such quick reviews presented Chris opportunities to revisit and uncover connections among previously learned characters. As Chris commented (in Interview 3), it allowed him to renew his interpretation of characters, further understand the meaning of semantic radicals and their role in the characters, and thus solidify his character memorization. The scheduled overlap and repetition of radicals across study sessions also made Chris feel impressed by how much he remembered and motivated him to continue the effort.

Despite his progress shown in the character writing section of the post-test (partially providing the characters rather than leaving blanks as he did in the pre-test), Chris expressed the desire for more progress. It could be that more study sessions are required beyond five weeks to see more significant progress. Chris also expressed the desire for supplemented handwriting practice in addition to 3D character tasks. He commented (in Interview 5), “I think that I needed to be more intentional in translating back from 3D to

2D. Like if the test had been putting the pieces together, I think I've done a better job than having to write it myself." This may have identified two missing links. One link was missed between component and stroke. In the 3D character project, the learner comprehended, memorized, and reproduced characters using the processing unit of component. In writing practice, learners would be required to additionally process at the stroke level. The other link was missed between the different reproducing levels of character composing and writing. While composing 3D components requires a learner to reproduce characters with building blocks provided, character writing requires further productive skills in order to introduce, stretch, and conclude individual strokes and form them in equidistant, connecting, and intersecting interconnections. The increased radical application skills gained from 3D character composing and networking tasks may be further utilized to increase the efficiency of writing practices, if such tasks are used in combination in varied format.

5.2.2 Presentation of 3D Characters

Throughout the study, the instructor and learner experimented for a best 3D character presentation in terms of dissection, size, weight, smoothness, and color. For most compound characters, their components are decomposition-ready once 3D printed out. For instance, once character 叫 is printed, its semantic component 口 and phonetic component 丩 are automatically separated since no strokes were adjacent or overlapped. Character 哪 automatically prints out three decomposed pieces, 口, 冄, and 阝. 3D printed integral characters remain as individual pieces. However, some compound characters, like 耷, consist of two or more adjacent radicals. The adjacent parts could be manually separated using a knife, but cutting leaves traces that gives out hint in character composing task. Digital pre-cut on Tinkercad would ensure better quality. Some other characters like 高, 馆, 照 are printed out with more than desired number of pieces. One may adjust the thickness of layer or use transparent material to connect the separated pieces as needed.

Throughout the 3D character project, Chris had continuously expressed his excitement about being able to touch, hold, and feel the written abstract symbols as 3D pieces, as it gave him a tactile, substantial, and satisfying feeling. The tactile pieces transformed a character composing task into a fun game putting together puzzle pieces. After testing out different printing dimensions, a character of 5 x 5 x 1 cm was found to balance size and weight with printing efficiency. Above a certain size separated strokes may become adjacent. For instance, two separate level strokes in 找 may merge to one line as in 找. It is better to 3D print complete characters and dissect them rather than printing out individual radicals, as the former retains accurate spatial configuration information of characters and components.

After testing all the colors provided (gold, black, and red) in the makerspace, red was picked to capture the learner's attention and because it is considered an auspicious color in Chinese culture. When 3D printing batches of characters, sticking to the same material, color, and size setting allows consistency of characters across study sessions. It allows task designs to select and mix characters previous used. When adopting the 3D character project in a classroom with more students, Chris suggested (in Interview 2) to further gamify the character composing task by presenting the 3D pieces in a bag. Chris also proposed an idea of 3D magnets to allow composition on other surfaces.

6. Discussion

This study explored an innovative utilization of 3D printing and demonstrated it as an effective means for Chinese character instruction. The results of the pre- and post-tests and end-of-session interviews aligned to suggest a prominent increase of learner's radical knowledge application upon completion of the 3D character project. Furthermore, by employing teacher-learner collaborative efforts in an iterative task design, this study demonstrated a methodology for innovative technology adoption.

6.1 3D Printing for Radical Awareness Development

The introduction of 3D printing triggered a series of changes in character presentation and processing, which facilitated character learning. The 3D presentation of characters shifted the processing unit of characters from handwritten strokes to tactile components. Chinese compound characters, once 3D printed, are naturally dissected into component pieces due to the visible diminutive space in between. However, such 3D pieces are not further decomposable since they are printed as whole. The 3D components form a tangible pathway between meaningless strokes and networks of characters. They transformed character learning from weaving strokes in handwriting, to placing individual components in the right orientation, relative position, and correct combination with others to form characters.

When processing at component level, additional haptic cues provided learners spatial information that facilitated their discovery of more in-depth configuration information at levels of individual component, component-component interaction, radical-character association, and character-character interaction. For individual components, the learner was more able to notice individual radical size, orientation, form variation, and typical position taken within a character. For component-component interaction, the learner was able to infer and retain in-depth information of their spatial relation. The tactile pieces provided the learner a hands-on Lego-like experience instead of mentally representing combinations of components. It presented the learner opportunities to not only recognize the configuration category (e.g., left- (middle-) right, top- (middle-) bottom, (half-) enclosed), but also make connections within the same configuration category. The learner was able to notice that even within the same configuration category, there is great variation in relative space shared by two components and interaction of stroke shape and number between two components in a compound character. For radical-character association, the learner's awareness of compositional logic was fostered. The role of radicals in a character was included in the interpretation of character compositions. When no transparent orthography was detected, the learner created his own meaningful interpretation to rationalize the compositional relations. For character-character interaction, 3D character radicals were used to engage the learner in character exploration and restructure character repertoire based on shared radicals. The character network via shared radicals offered an organized way for effective information processing.

6.2 Collaborative and Iterative Task Design

The adoption of 3D printing technology reshaped the character learning and opened up exciting possibilities for innovative task designs by incorporating haptic cues. Based on the results of this exploratory case study, a task series consisting of four parts is recommended: i) a *3D character composing task* where a learner recomposes the mixed 3D components into characters; ii) a *radical knowledge and component relation session* where a learner is guided to discover the sound, shape, and meaning of common semantic radicals as well as their role in compound characters; iii) a *character network building* session that restructures character repertoire by exploring unknown characters and reviewing learned ones that share the same radicals; and iv) *character handwriting practice* which facilitates a learner to apply radical awareness in producing complete or partial characters. Additionally, considering the positive effect of applying a combination of character learning practice (Xu & Padilla, 2013; Xu et al., 2013; Chen et al., 2013), an instructional design may be tailored to students' needs and by adding reading practice, writing practice, and multimedia instruction utilizing text, image, animation of stroke-sequenced-animation, and pronunciations.

This task design was the result of a student-teacher collaborative effort, which may be applicable to other task designs incorporating innovative technology. As an exploratory endeavor to apply 3D printing technology in Chinese character teaching, this study encountered many unknowns in the task design and its instructional effects. This study started with reviewing the definition and operationalization of radical awareness as well as previous instructional endeavors to facilitate its development. Based on the literature, the researcher/instructor designed a 3D character project to focus on bridging the gap between radical knowledge and its application. The learner superimposing and reinterpreting tasks was fully acknowledged as the dynamic interaction between task-as-workplan and task-in-process to engage both instructor and learner in an iterative process of task co-construction. By allowing the learner to reflect on his performance and strategy at the end of each study session, the instructor was able to elicit how the 3D printing affected Chinese character learning. The learner was also invited to share suggestions to instructional design. The instructor was thus able to take learner's suggestions and interpret them in the framework of radical awareness operationalization. The updated task design was then promptly tested in class and iterated via further reflection. By engaging the learner in the iterative design of task-in-progress, the learner showed more agency in learning. Chris maintained his curiosity and excitement throughout the 3D character project and was always looking forward to the next session. Finally, after iterative revision, a 3D character task series was suggested for future character learning and teaching.

7. Conclusions

This case study explored the task design and instructional effects of adopting 3D technology in Chinese character learning and teaching. The character tasks mediated with 3D printing technology positively affected learner's radical knowledge and application skills through radical-character association. The introduction of 3D printing reshaped the learning unit of character from stroke to component, which enabled task design to direct learners to further notice the size, meaning, variation, in-depth configuration, and compositional logic of components, and to restructure character network via radicals. This study demonstrated a method of incorporating innovative technology via the collaborative and iterative efforts of both instructor and student.

Results of this study should be interpreted within its limitation of a case study. As an exploratory case study, this project took the first step to provide a foundation for future research. By recruiting more participants, future instructional design will be able to recognize and address the needs of a more diversified student body with varied language aptitude, experience, learning styles, and cognitive skills. By expanding the scope of 3D character tasks, functional non-radical components can also be included in pedagogical design. A controlled design would provide a closer look at the specific effects of 3D character learning and its applicability in different contexts. With more study to incorporate the character learning component at the course and curriculum level, a longitudinal study beginning the end of first year through the end of second year would provide a look into the effects of 3D character learning across the radical knowledge application developmental plateau.

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Appendix A Characters and Targeted Radicals of Each Study Session

Session	Characters	Targeted radicals
1	请、贵、呢、朱、茶、红、菜、图	讠、贝、口、纟、艹、囗
2	叫、名、国、找、友、话、高、姐	口、夕、囗、讠、扌、女
3	哪、耷、他、明、点、李、馆、课	阝、耳、亻、日、灬、子、饣、讠
4	病、打、晚、她、忙、看、男、跑	疒、扌、日、女、忄、目、田、𧾷
5	歌、问、去、想、字、聊、洗、起	欠、门、心、宀、耳、氵、走

Appendix B Pre-test

Part 1/4. Choose the structure of the characters (from ABCD) and write out their radicals/components. (20 points)

A. Left- (middle-) right **B.** Top- (middle-) bottom **C.** (Half-) enclosure **D.** Integral

姐( ) ________________	男( ) ________________	做( ) ________________
过( ) ________________	聊( ) ________________	哪( ) ________________
字( ) ________________	国( ) ________________	两( ) ________________
不( ) ________________	学( ) ________________	照( ) ________________
图( ) ________________	律( ) ________________	意( ) ________________
可( ) ________________	王( ) ________________	问( ) ________________
医( ) ________________	女( ) ________________	

Part 2/4. Write down the meaning of the given radical. (30 points)

人(亻) ______________	刀(刂) ______________	力______________	女______________
口______________	囗______________	大______________	小______________
子______________	心______________	手(扌) ______________	日______________
月______________	木______________	水(氵) ______________	火(灬) ______________
疒______________	辶______________	田______________	目______________
糸(纟) ______________	耳______________	言(讠) ______________	贝______________
走______________	足(⻊)______________	金(钅) ______________	门______________
雨______________	食(饣) ______________		

Part 3/4. a. Circle the character best fits the meaning provided in English based on their radicals. (10 points)

1. Attendant: 恃 峙 侍 2. Silver: 银 恨 痕 3. To water: 烧 饶 浇
4. To peak: 嫖 瞟 膘 5. To stroll: 逛 诳 俇 6. To step: 跨 垮 刳
7. To drive: 驾 架 痂 8. Raw silk: 绡 捎 削 9. Imperial concubine: 妃 纪 忌
10. To bribe: 贿 囿 痏

b. Provide the missing radical of each character based on the English meaning given. (20 points)

1. Hot: 执 2. Poem: 寺 3. To cure: 了 4. Companion: 半 5. Orchid: 惠
6. To enclose: 韦 7. To shout: 咸 8. Child: 亥 9. To ponder: 田 10. To lift: 是
11. Shining: 翟 12. Lake: 胡 13. Tree: 对 14. To sleep: 垂 15. To go to: 卜
16. Stagger: 册 17. Dumpling: 交 18. Fortune: 才 19. Deaf: 龙 20. To embroider: 秀

Part 4/4. Write the character with the pinyin and English provided. (30 points)

qǐng (please) ____	guì (expensive) ____	ne (end-of-the-sentence particle) ______
chá(tea) ______	hóng (red) ______	cài (dish) ______
tú (picture, as in túshū guǎn) ______	jiào (call) ______	míng (name) ______
zhǎo (look for) ______	huà (words) ______	gāo (tall) ______
jiě (elder sister) ______	nǎ (where) ______	tā (he) ______

Appendix C Post-test

Part 1/4. Choose the structure of the characters (from ABCD) and write out their radicals/components. (20 points)

A. Left-(middle-) right **B.** Top-(middle-) bottom **C.** (Half-) enclosure **D.** Integral

呀( ) ______	大( ) ______	书( ) ______
绍( ) ______	谢( ) ______	家( ) ______
才( ) ______	常( ) ______	因( ) ______
高( ) ______	同( ) ______	起( ) ______
开( ) ______	这( ) ______	星( ) ______
下( ) ______	馆( ) ______	觉( ) ______
上( ) ______	咖( ) ______	

Part 2/4. Write down the meaning of the given radical. (30 points)

人(亻) ______	刀(刂) ______	力______	女______
口______	囗______	大______	小______
子______	心______	手(扌) ______	日______
月______	木______	水(氵) ______	火(灬) ______
疒______	辶______	田______	目______
糸(纟) ______	耳______	言(讠) ______	贝______
走______	足(⻊)______	金(钅) ______	门______
雨______	食(饣) ______		

Part 3/4. a. Circle the character best fits the meaning provided in English based on their radicals. (10 points)

1. nail 钉 顶 叮 2. soup 肠 汤 疡 3. leap 趵 钓 讨
4. muscle 肌 讥 饥 5. beautiful 嬛 寰 擐 6. greedy 贪 含 衾
7. remote 迢 沼 岧 8. scar 疤 笆 杷
9. footman 仆 补 扑 10. weft 围 尾 纬

b. Provide the missing radical of each character based on the English meaning given. (20 points)

1. To cook, to boil: 享 2. To talk: 井 3. To be ill: 丙
4. To serve (as a servant): 司 5. luxuriant growth of fragrant grass: 萋
6. To be prisoned: 人 7. To roar: 孔 8. orphan: 瓜 9. angry: 奴 10. To pick up: 佥
11. Dry in the sun: 西 12. River: 可 13. Pine tree: 公 14. To blink: 乏
15. To walk with spirit: 丩 16. To halt feet: 主 17. Round flat cake: 并
18. To compensate: 音 19. To listen tentatively: 令 20. Thin strong silk: 肙

Part 4/4. Write the character with the pinyin and English provided. (30 points)

diǎn (dot, to point, to order) ______ lǐ (plum, last name) ______
guǎn (a venue/location for restaurant, library) ______ guó (country) ______
kè (class, course) ______ bìng (to be ill) ______ wǎn (late) ______
tā (she) ______ máng (busy) ______ pǎo (to run) ______ gē (song) ______
wèn (to ask) ______ xiǎng (to think) ______ zì (character) ______ liáo (to chat) ______

