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MakeBronze: An interactive system to promote Chinese bronze culture in children through hands-on experience with lost-wax casting

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ABSTRACT

Chinese bronze is a significant symbol of Chinese rich history and culture. However, disseminating bronze culture to children is challenging due to the lack of effective approaches to engage them. A survey of 467 Chinese children showed that their knowledge of bronzes primarily comes from traditional teaching methods, such as books and exhibitions. Hands-on opportunities for children to interact with bronzes and experience how they were made thousands of years ago are rare. Therefore, we designed MakeBronze, an interactive system mainly composed of a robotic arm, a drawing tablet, and cameras to allow children to experience the lost-wax casting and create their own artifacts. A study with 60 children showed that MakeBronze could better help them understand the fabrication process and raise their interest in bronze culture. Our work offers insights into how technologies that are easily accessible to children can be exploited for bronze culture preservation.

1. Introduction

Bronze is the earliest artificial alloy consisting primarily of copper and tin. The emergence of sophisticated bronze artifacts benefits from the development of casting technology, which is also a significant symbol of human civilization. Unlike bronzes of most other countries created as tools or decorations, Chinese bronzes often acted as ritual artifacts, which closely connected with the economy and culture of that time, far beyond their general practical functions (Rawson, 1987). Moreover, their changeable shape, exquisite patterns, and varied inscriptions are of great aesthetic and historical value. Typical representatives include Marquis Yi's Chime-Bells (Fig. 1(a)) and Marquis Yi's Plate (Fig. 1(b)).[1] Therefore, teaching children about the bronze culture has been an excellent approach used by Chinese parents and schools to impart the nation's rich history and traditional culture (Chunyan, 2015).

Bronze culture encompasses several aspects, such as the appearance of bronze artifacts, applications, and the historical narratives associated with them and so on. The transmission of these information to children commonly occurs through acquisition (Krashen, 1981), which commonly involves various methods such as instruction delivered by the teacher (Vasalou et al., 2022), lectures, face-to-face presentations, videos, etc (London, 2017). Acquisition is often an educator-led process of organizing information (Brown, 2023), and is currently widely used for cultural heritage preservation in China. Moreover, the casting process is also an important part of bronze culture, which is difficult for children to learn because the principles usually involve knowledge from multiple subjects. We can further provide children with hands-on opportunities in accordance with the constructivist theory (Mascolo et al., 2005), help them understand the process more directly and provoke their thinking (Dewey, 2012), which is very beneficial to their learning. However, according to our survey of 467 Chinese children (See Section 3.2), the existing ways children learn about the Chinese bronze culture are mainly reading books, watching videos, or sometimes attending exhibitions. There is a significant lack of opportunities for children to gain hands-on experiences to make or interact with bronze artifacts. One significant factor contributing to this phenomenon is that creating bronze artifacts can be dangerous due to the need for the children to be exposed to tools and materials at high temperatures during the casting process.

In this paper, we present MakeBronze, an interactive system designed for children to experience the fabrication process of bronzes and create their own artifacts. The MakeBronze system consists of several

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[1] Marquis Yi's Chime-Bells and Marquis Yi's Plate are currently stored in Hubei Provincial Museum, China.

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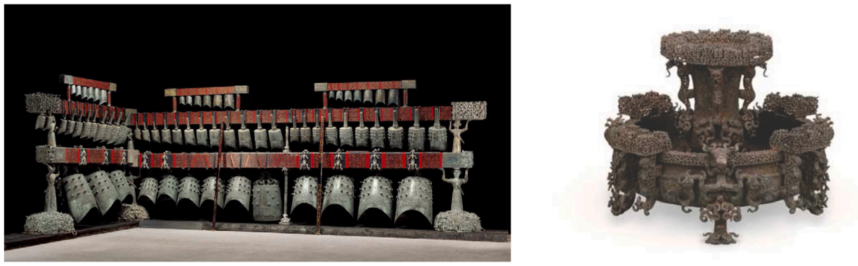


(a) Marquis Yi's Chime-Bells (b) Marquis Yi's Plate

Fig. 1. Two Representative Chinese bronzes. (a) Marquis Yi's Chime-Bells. It is the biggest bronze musical instrument in the world. (b) Marquis Yi's Plate. It a typical product made by the lost-wax casting.

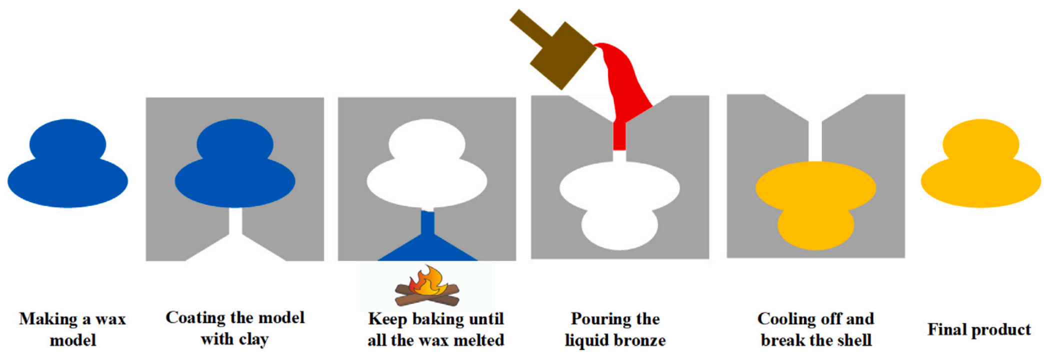


Fig. 2. An illustration of lost-wax casting.

components including a robotic arm, a drawing tablet, a motion gesture sensor, an oven, two monitors, and cameras. Its primary purpose is to replicate the classic lost-wax casting technique employed in ancient times (See Section 4.2), while ensuring the safety of children by minimizing their exposure to heat. Through a user study with 60 Chinese children, we proved that our system could better help children understand the process of lost-wax casting than the traditional learning method and raise their interest in bronze culture. Our work has enabled the dissemination of bronze culture through multisensory learning with the help of devices that are accessible to children such as tablets and robotic arms, and this effective approach offers insights into how interactive technology can be exploited for cultural preservation. The aims of this paper are: (1) to present a novel interactive system that safely affords children hands-on experiences of ancient bronze casting; (2) to explore the impact of multisensory learning assisted with a novel interactive system on children's learning efficiency compared to traditional learning methods such as lessons, and (3) to investigate the design requirements of interactive systems for children.

The main contributions of our work are as follows:

(1) The result of a survey with 467 Chinese children suggested that the bottleneck of disseminating bronze culture among children is that the existing methods do not effectively develop their interest or motivate them to explore the bronze culture.

(2) The MakeBronze system was developed, composed of a robotic arm and devices that are easily accessible to children, as a fun and safe way to learn and experience ancient and risky lost-wax casting. A user study with 60 children has shown that our system can help increase their interest in Chinese bronze culture.

(3) Through MakeBronze, a multisensory learning system assisted with interactive technologies, we have investigated the advantages of multisensory learning to improve children's learning efficiency of bronze casting. Through in-depth interviews, we obtained an insight into children's requirements, guiding the design of subsequent multisensory learning systems for children.

2. Background and related work

2.1. Bronze casting techniques and inscriptions

There are two types of casting techniques for bronzes, namely lost-wax casting and multi-mold casting. The scientific archaeological excavations revealed that multi-mold casting has a longer history than lost-wax casting in China. The earliest bronze artifact ever discovered in China was a Majiayao Type bronze knife created by multi-mold casting discovered in Gansu Province (Yunxiang, 2003). During the Shang and Chou dynasties (1600 B.C.–256 B.C.), multi-mold casting had ever been used to produce some bronzes with complicated shapes successfully, but it faced a significant challenge as the design of bronze became more and more sophisticated (Zhu, 1995). In contrast, lost-wax casting (See Fig. 2) is better suited for small objects or those with irregular shapes and intricate designs since wax is relatively easy to carve into exquisite patterns (Bavarian and Reiner, 2005). A representative antique cast by the lost-wax method is the Marquis Yi's Plate (See Fig. 1(b)).

Lost-wax casting consists of five steps (Zhu, 1995):

Step 1. Make a model of the desired bronze product using fusible materials, such as beeswax.

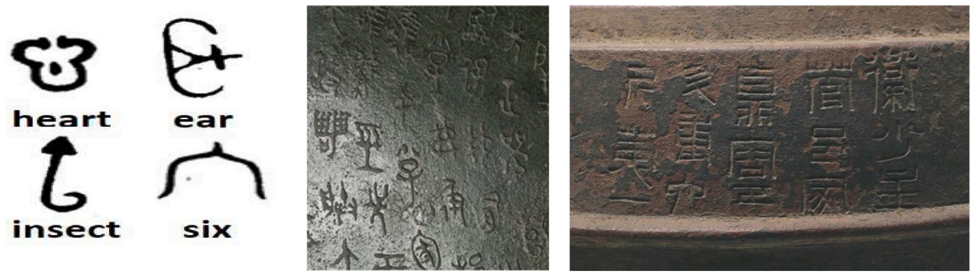
Step 2. Cover the wax model with liquid clay multiple times to form a shell on the surface of it.

Step 3. Bake until the wax model is melted and flows out of the shell to create a hollow shell.

Step4. Pour the liquid bronze into the shell and wait for it to cool off.

Step5. Break the shell and get the bronze.

Chinese bronze inscriptions are characters written on ritual bronze from the Shang Dynasty. The inscriptions recorded owners' names, important events, or some statements related to reward or sacrifice (Wang, 2018), which bring bronzes great historical value. Inscriptions can also be used to date bronzes because they have changed over time in font, layout, and content. In the early days, bronze inscriptions were hieroglyphs (See Fig. 3(a)). The length of inscriptions also increases



(a) Characters of inscriptions(Geng, 1985) (b) Zhu Ming (c) Ke Ming

Fig. 3. Examples of bronze inscriptions in the early days and two types of inscriptions. (a) Example of inscription characters (Geng, 1985). (b) "Zhu Ming" means the characters had been formed on the model before casting. (c) "Ke Ming" means the characters are engraved after the bronze was cast.

over time. For example, the number of characters on bronzes is less than one hundred in the Shang Dynasty. Nevertheless, in the Chou Dynasty, it became longer, with the longest up to around 500.[2] There are two types of inscriptions on bronzes (Zhu, 1995): "Zhu Ming" (See Fig. 3(b)) and "Ke Ming" (See Fig. 3(c)). "Zhu Ming" means the characters had been formed on the model before casting, while "Ke Ming" means the writing is engraved after the bronze was cast (Qiu, 1988).

2.2. Cultural heritage preservation with interactive technology

There has been a growing interest in the cultural heritage preservation with interactive technology. The work can be roughly divided into two categories based on the type of interface: Graphical User Interface (GUI) and Tangible User Interface (TUI).

Graphical user interfaces have been quite popular in recent years, especially with the use of Augmented Reality (AR) and Virtual Reality (VR) technologies, allowing users to interact with or virtually tour cultural heritage. Kobayashi proposed an AR system that would use motion-image projection and image recognition to mimic the wrapping process of a piece of traditional Japanese furoshiki (Kobayashi et al., 2019). Jin designed a virtual reality learning environment to reconstruct traditional Chinese paintings (Jin et al., 2020). Wojciechowski developed a system based on VR and AR technologies to observe the 3D model of the relics, which allows designers to quickly set up a virtual exhibition (Wojciechowski et al., 2004). MRGuqin is a mixed virtual reality system, which is designed to teach beginners to play Guqin (a traditional Chinese instrument), ease the learning process and enhance confidence (Yu et al., 2021). Brown developed a system in which people can remotely visit the museum through a VR device and interact with all remote visitors and in-person visitors (Brown et al., 2003). Gaitatzes created a system allows for a virtual journey of Miletus, an ancient city by the coast of Asia Minor (Gaitatzes et al., 2001). The connection between the digital and physical worlds is made possible through **tangible user interface**, which is also employed to preserve cultural heritage. Tangible User Interface can be used to connect the digital and physical worlds, which is also applied to cultural heritage preservation. StoryBeads (Reitsma et al., 2013) is a tangible record and playback device designed to preserve the cultural heritage of BaNtwane (a South African tribe) through oral storytelling. Mapping Place (Chu et al., 2015) is a tangible tabletop installation piece designed for a museum exhibition contrasting. It enables visitors to learn and understand symbolic and nonlinguistic mapping concepts that are central to Lukasa by creating and sharing stories with others. Kwan presented three tangible prototypes centered on the history and use of Western European boxwood prayer-nuts, through a 'multimodal' ensemble of visual, aural, tactile, and olfactory interactions (Kwan et al., 2016). Actually, studies conducted by Eardley proved that multisensory tools can enhance visitor engagement with museums (Eardley et al., 2018). Multisensory approaches have also been commonly used in museums to improve the user experience or educate children (Garzotto et al., 2020). Chianese designed an Internet of Things (IoT) architecture that supports the designing of a smart museum, and a real case of the study had been placed in a temporary art exhibition of sculptures in the Maschio Angioino Castle (Chianese and Piccialli, 2014). Ardito proposed the End-User Development method that can support cultural heritage experts to create customizable visit experiences in museums and other cultural sites (Ardito et al., 2018b,a), allowing visitors to acquire cultural heritage content while interacting with the surrounding smart environment and the smart sensors included in it. However, to the best of our knowledge, existing cultural conservation efforts using interactive technologies have not focused on the fabrication process of bronzes, which is an important component of Chinese bronze culture.

2.3. Digital fabrication of traditional crafts

Digital technology is currently employed to make some traditional crafts, with Computer-Aided Design (CAD) and 3D printing being the most popular methods. The EscapeLoom system (Deshpande et al., 2021) assists users in designing prototypes with the complex 3D geometric scheme through specific visualization software and combines 3D printing equipment to produce personalized hand-weaving artifacts with different shapes, patterns, and functions, to provide a new knitting experience. Zoran used 3D printing technology to enhance the artistic features of traditional crafts, such as hand-knitting (Zoran, 2013), ergonomic design of musical instrument (Zoran, 2011) and artifact restoration (Zoran and Buechley, 2013). He also held a Hybrid Craft exhibition (Zoran, 2015) which showcased several hybrid projects of contemporary making and traditional crafts. Padfield explored the possibility and synergy of the combination of traditional craft and digital technology, cooperated with several experienced craftsmen, combined with a 3D printer and Computer Numerical Control (CNC) apparatus, and produced glass-blown crafts with more complicated shapes (Padfield et al., 2018). Jacobs also designed and made a kind of jewelry in Ju/'hoansi cultural (A small foraging society living in Namibia and Botswana) by combining digital technologies such as computer numerical control, CAD, and 3D printing (Jacobs and Zoran, 2015). PatchProv (Leake et al., 2021) is an improvisational design system to assist in sewing. Users can randomly combine fabric swatches of different shapes and colors to design their patterns and create physical solid textiles. Deepshikha chose to use smart materials such as electronics instead of traditional precious materials as part of the design elements embedded into the fabrication process that makes textile crafts dynamic (Deepshikha and Yammiyavar, 2018). Efrat proposed Hybrid Bricolage (Efrat et al., 2016), a new parametric design paradigm using a fixed set of computer-generated, tweakable meta-patterns, which can assist the design process of smocking by visualizing the pattern and

[2] Duke Mao Tripod, which has an inscription of about 500 characters arranged in 32 lines, currently at the National Palace Museum in Taipei

mark fabrics with a laser cutting machine. Although these methods can enhance traditional crafts fabrication, they are designed for experts who already have professional knowledge or skills, which hardly assist in publicizing relevant culture to the general public.

2.4. Bronze protection with digital technology

There are some efforts in protecting bronzes with digital approaches, most of which are concerned with the recognition of the content inscribed on bronzes and the restoration of antiques. Kuang proposes an end-to-end bronze inscription object detector based on deep learning, which can automatically and completely detect the position of bronze inscription (Kuang et al., 2020). Han presented a non-destructive hyperspectral imaging method for restoring the painted patterns on bronze chariot (Han et al., 2020). Zong presented a method for characteristic profile recognition, which was used to recognize and repair the characteristics of bronze decorations (Zong, 2021). Masuda proposed an automatic method for detecting the shape difference between a pair of ancient mirrors (Masuda et al., 2003), which may offer a clue for the exact location of Yamatai State. Meanwhile, 3D scanning is widely used in the preservation of bronzes. Lee carried out 3D scanning of bronze cultural relics to obtain the shape and color information of the original data, and combined with 3D modeling to repair the missing or damaged areas in the original data, then the generated 3D model was rendered to a restored image (Lee et al., 2011). Jo proposed a non-contact bronze cultural relic replication method, which digitized the bronze mirror by scanning and converted it into a voxel model to record the digital data of the bronze mirror with high accuracy, and completed the reconstruction work of the bronze mirror by Boolean modeling (Jo and Lee, 2021). Tang applied 3D scanning and point cloud data processing technology to reconstruct and restore damaged bronze artifacts from excavation (Jian-yin et al., 2019). However, these studies were pure software methods, and do not provide hands-on opportunities to interact with bronzes.

2.5. Multisensory learning for children

Many research efforts have demonstrated that multisensory interaction can effectively support and enhance children's learning. Lindgren presented a whole-body interactive simulation to help middle school students to learn about gravity and planetary motion, and the effective was proved by comparing with students who only use a desktop version of the same simulation (Lindgren et al., 2016). Kang studied how students engaged with an embodied mixed-reality science learning simulation using advanced gesture recognition techniques to support full-body interaction (Kang et al., 2018)). Jewitt was focused on the touch of multisensory learning, presented and discussed how multimodality might engage newly with touch from a multimodal and multisensory study of participants interacting in VR experiences (Jewitt et al., 2021)). Price developed a pedagogical framework to illustrate that the theory of learning (pedagogical underpinning) leads to consideration of instructional strategies that involve the 'body', through a multisensory serious games design, which is also informed by appropriate mathematical metaphors and technology design guidelines, in building meaningful connections between physical action and concepts in early years' mathematics (Price et al., 2017)). By introducing physical interactions, these works allow children to be more engaged in the learning process, rather than just passively receiving knowledge. These efforts inspired us to incorporate physical interactions into cultural preservation applications such as traditional crafts heritage for children, by giving them hands-on opportunities to provoke thinking and assist their understanding.

3. Survey

In order to better publicize bronze culture to children, a survey was conducted to understand the current approaches of disseminating the bronze culture among them.

Table 1
The way the child learned about bronzes (Multiple choices). Traditional paper materials are still the predominant source of bronze culture for children.

	Number of children	Ratio
Paper materials	290	73.8%
Videos or Exhibitions	183	51.7%
Interactive systems	15	3.8%

3.1. Participants

We recruited 467 elementary and middle school students nationwide to participate in an online survey, ensuring all provinces of China were covered. Participants included 257 boys and 210 girls, ranging in age from 6 to 15, with an average age of 10.25. Children between 6 and 15 years old usually can express their thoughts clearly in words and have more free time to spend on extracurricular studies than high school students who are typically older than 15 years old.

3.2. Questionnaire

The questionnaire consists of four questions as follows. Only the participants who indicated an affirmative response to the first question, were asked to answer the subsequent questions. *Q1*, *Q2*, and *Q3* were intended to assess the popularity of bronze culture among children, whereas *Q4* was designed to evaluate the effectiveness of existing methods for improving children's interests in the bronze culture.

Q1. Have you ever heard of Chinese Bronze before?

Q2. How did you learn about Chinese Bronzes? (Participants can provide more than one answer.)

Q3. Which aspect of Chinese bronze culture did you learn the most from the methods you stated above?

Q4. Have you ever tried to learn more about Chinese bronze culture proactively after you learned about it through the aforementioned methods?

3.3. Result

Q1: 74 children claimed that they had no prior knowledge of bronzes, accounting for 15.9% of the participants, while 393 children (84.1%) said they had heard of them.

Q2: Participants who reported in *Q1* that they have knowledge of Chinese bronzes were subsequently asked to provide more information on the sources from which they acquired their understanding of the bronze culture. They were permitted to report multiple methods. The result is presented in Table 1, indicating that the predominant approach was the utilization of paper-based resources. 290 children said they learned about the bronze culture from reading books, magazines, and newspapers, accounting for 73.8% of the overall replies. Watching videos and visiting exhibitions, which is more intuitive than paper materials, accounting for 45.6% of all the responses (183 children). Only 15 children (3.8%) had interacted with the digital 3D model of bronzes using electronic devices such as cellphones or computers.

Q3: The Chinese bronze culture has several important aspects, including historical facts, artistic values, and fabrication methods. We would like to know which of these is most widely disseminated among children. The result indicates that the history of bronze artifacts is the most common topic presented to children. Meanwhile, fabrication method, appearance and application accounted for 17.6%, 9.9% and 5.3% respectively (See Table 2.). Appearance includes shape and pattern. Application refers to the intended usage or function of an object, such as musical instruments, containers, etc.

Q4: For those children who had heard about Chinese bronzes, we wanted to know which teaching method would enhance their interest in bronze culture, by asking them if they were motivated to further explore bronze after learning through this method. The results are showed in Table 3:

Table 2
Four important aspects of Chinese bronze culture. The aspect most publicized among children is history, followed by fabrication method, appearance and application.

	Ratio
History	67.2%
Fabrication method	17.6%
Appearance	9.9%
Application	5.3%

Table 3
The number of children who were interested and not interested in continuing to learn about bronzes after being taught through different methods and their ratio. The existing interactive systems related to bronzes are rare, but they suggest a trend that more children will develop an interest in bronzes culture after being exposed to an interactive learning environment.

	Interested	Not interested	Ratio
Paper materials	173	117	≈ 1.5
Videos or Exhibitions	108	75	≈ 1.4
Interactive systems	12	3	≈ 4

1. For those who learned from paper materials (290 children in total), 173 of them chose "YES", while 117 children admitted they did not try to learn about bronzes proactively (chose "No").

2. From videos or exhibitions (183 children in total), 108 of them chose "YES", while 75 children chose "No".

3. From interaction systems (15 children in total), 12 of them chose "YES", while 3 children chose "No".

Moreover, we calculated the percentage of children who were interested and not interested in continuing to learn about bronzes after being taught through different methods. The proportion of interactive systems is the highest, followed by paper materials, then videos or exhibitions.

3.4. Analysis

The result of ***Q1*** revealed that a significant proportion (84.1%) of the children had heard of Chinese bronzes. The potential reason might be attributed to the inclusion of Chinese bronzes in the textbooks, which confirms the importance of bronze culture. However, it should be noted that having heard of bronzes does not always imply a comprehensive understanding of their historical and cultural significance, so we asked subsequent questions.

The results of ***Q2*** indicated that traditional methods like reading paper materials, watching videos, or visiting museums were still the major sources for children to learn about bronze. Although bronze could be made into containers or tools, they are no longer accessible in daily life as bronze has been replaced by lighter and more durable materials. Therefore, bronze vessels are only kept in museums and cannot be seen on a daily basis, children have little opportunity to touch or use them. According to the result, few children learned about the bronze culture through interactive technology due to the lack of interactive systems designed specifically for children's usage.

The results of ***Q3*** showed that children were more likely to acquire knowledge about history while learning about the bronze culture. Other important aspects, such as fabrication method or appearance, which represent the development of technology in ancient China, were not well presented to children. It is probably because, compared to historical stories, understanding the fabrication method requires some technical and cultural knowledge and is more difficult for children, resulting in publicity materials for them often only involving history. The application of bronze is introduced less probably because there is a big difference in lifestyle between nowadays and ancient China, and the household items once used may no longer be necessary or even eliminated, so it is not easy for children to understand.

Raising children's interest in learning is also crucial for better teaching them the bronze culture. If the previous way of learning about bronze (e.g., reading books or visiting exhibits) enhances their interest in bronze knowledge, they will answer "yes", and conversely will answer "no". While the number of samples is unbalanced with significantly fewer in the interactive systems category, the result of ***Q4*** suggested a trend that more children will develop an interest in bronze culture after being exposed to an interactive learning environment, which is consistent with the findings from other domains (Cheng et al., 2017; Kaufmann et al., 2000; Sapounidis and Demetriadis, 2013).

To the best of our knowledge, the existing interactive systems related to bronze culture mainly focus on displaying 3D models or images of bronze artifacts (UNESCO, 2020; Museum, 2021a,b). There is a missing opportunity to provide children with cultural experiences beyond observing. We believe that allowing children to touch, play with, or even create their own bronze artifacts may offer a more immersive and rewarding experience, thus potentially deepening their understanding and interest in the bronze culture. Therefore, we designed MakeBronze, an interactive system that enables children to safely experience the fabrication process and create their artifacts using lost-wax casting, a technique that had been used in ancient China.

4. MakeBronze system

The MakeBronze system is designed to provide children with a hands-on opportunity to experience the fabrication process of bronzes with interactive technology, enhance their interest in learning more about bronze culture, and thus publicize bronze culture. The hands-on experience, which assists children in multisensory learning, has been confirmed by previous works (Lindgren et al., 2016; Price et al., 2017) to be effective in supporting and improving children's learning. Our system faces three challenges:

(1) To fit the size of children's hands, the product's dimensions should be restricted. Small artifacts are easier for children to create and play with;

(2) Unlike other traditional crafts mentioned in Section 2.3, bronze casting often involves high-temperature operations that are dangerous for children;

(3) In order to make it accessible to more children, MakeBronze needs to be easy-to-build.

4.1. System design

4.1.1. Design concept

Three design principles corresponding to the aforementioned challenges are proposed:

P1: The casting method that MakeBronze imitated is suitable for small items, and the size of products will be restricted.

P2: MakeBronze needs to keep children away from the heat.

P3: The components of MakeBronze are off-the-shelf.

The MakeBronze system (See Fig. 4) is designed in accordance with these principles. Lost-wax casting is adopted because it is more suitable for producing small artifacts than multi-mold casting, as has been mentioned in Section 2.1 (for ***P1***). The dimensions of the wax models produced by our system should be constrained (for ***P1***). Due to the inherent risks associated with the high temperatures involved in the melting and pouring of liquid wax and metal, a robotic arm is employed to execute these duties in a manner familiar to children (for ***P2***). In addition, the raw materials used in the system are substituted with a fusible alloy and plaster. (for ***P2***). It is imperative that all components of the system should be accessible for purchase (for ***P3***).

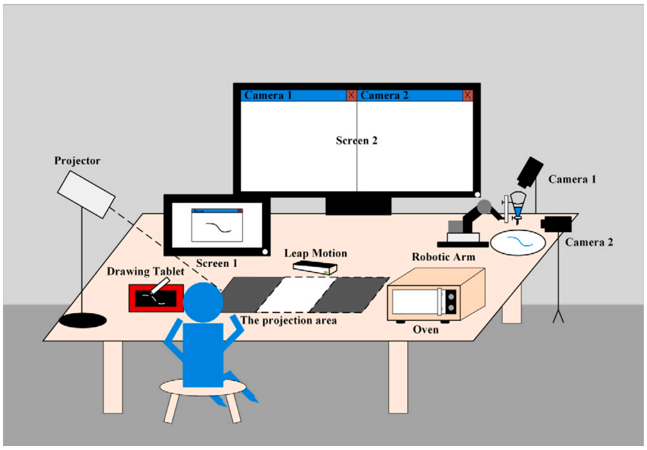


Fig. 4. The illustration of the MakeBronze system. It is an interactive system designed for children to experience lost-wax casting and create their own artifacts in a safe way.

4.1.2. Raw material selection

The liquid bronze and liquid clay used in traditional lost-wax casting (Zhu, 1995) were replaced by the fusible alloy and plaster respectively.

(1) The bronze needs to be heated to 800°C to melt, which is dangerous for children to operate. Therefore, we decided to employ a fusible alloy which is off-the-shelf and harmless to replace the bronze. Due to its low melting point (95°C), common appliances like ovens can be used to melt it into liquid. The fusible alloy is silver, which differs from the golden color of bronze (The bronze antiques seem green now because of rusting), but the replacement of the raw materials has no impact on learning the fabrication process.

(2) The liquid clay was substituted with plaster to form shells, which speeds up the shell's curing time.

4.1.3. Fabrication process

The process of lost-wax casting can be divided into three major steps: (1) Making a wax model for the target object, (2) Coating the wax model with clay, then melting the wax model for a clay shell, and (3) Pouring the liquid bronze into the shell.

Accordingly, the fabrication process of the MakeBronze system are divided into three stages: **Stage 1** involves the creation of a wax model, followed by **Stage 2** which entails the melting of the wax to generate a hollow shell. Lastly, in **Stage 3**, the liquid alloy is dropped into the hollow shell to produce the final result.

Stage 1: Making the wax model

Two modes are provided in Stage 1 (See Fig. 5):

(1) Aiming mode. In this mode, there are several candidate silicone molds for children to choose from. Children are required to drop liquid wax into a silicone mold using a robotic arm. It yields a wax model after it cools. After that, the wax model will be retrieved and trimmed.

(2) Free mode. To enrich the products and optimize children's feelings, they are encouraged to use the robotic arm to draw their favorite graphs. In this mode, the liquid wax is dropped continuously onto a plate along with the movements of the robotic arm. A wax model, the same as the trajectories the child draws, is then created. Then, it will be trimmed when cooled off.

During this stage, children will acquire knowledge regarding the rapid solidification of wax at room temperature, as well as its softness, which facilitates the creation of intricate shapes through carving.

Stage 2: Melting the wax model

At this stage, we provide an instructional video for the child to follow. In order to minimize the difficulty of imitating the operations in the video, it needs to be played synchronized with the actual progress made by the children. So we split the instructional video into three clips, allowing children to adjust the speed as needed, i.e., they switch to the next video clip on their own only when the instruction in the current video has been completed. The three clips are: (1) Mixing water and plaster powder; (2) Covering the wax model with plaster; (3) Placing the plastered wax model into an oven and waiting for the wax model melted to get a plaster shell.

Children will learn in this stage that the application of heat accelerates the solidification process of plaster. Moreover, it is noteworthy that wax possesses a lower melting point in contrast to plaster. Consequently, when heated to a temperature between the melting point of wax and that of plaster, the wax will melt into liquid, thus creating a cavity inside the plaster, which faithfully replicates the shape of the original wax model.

Stage 3: Dropping the liquid alloy

In this stage, children manipulate the robotic arm to drop liquid alloy into the shell formed in Stage 2. After the alloy solidifies, the plaster shell is smashed to obtain a metal model as the final product.

Children will discover that plaster is more fragile than the fusible alloy, leading to the understanding that breaking plaster will have little impact on the final product.

Through the utilization of this system, children will get comprehensive knowledge of the entire process of lost-wax casting, as well as its principles.

4.2. Prototype

The prototype of the MakeBronze system (in aiming mode) is illustrated in Fig. 4. It is composed of a robotic arm, a drawing tablet, a projector, a motion gesture sensor, an oven, two monitors, and two cameras. Separatory funnels containing liquid wax or alloy are fixed to the robot arm. An experienced assistant will help open and close the stopcock of the separatory funnel, controlling the flow of the liquid wax or alloy. This process needs to be carried out manually currently, while we plan to make it automatically in the future. Moreover, we developed an application software with GUI to help children control the robotic arm via the tablet, fitting the children's usage habits — drawing on a tablet is similar to drawing on paper as they usually do. In this section, we will introduce our prototype aligning with each stage of the designed fabrication process (See Section 4.1.3).

Stage 1

The equipment used in Stage 1 includes a drawing tablet, a robotic arm, two monitors and two cameras. Two cameras are oriented towards the robotic arm orthogonally (See Fig. 5). The video stream captured by the cameras is shown on screen 2, and the graphs drawn on the tablet are shown on screen 1 (See Fig. 4).

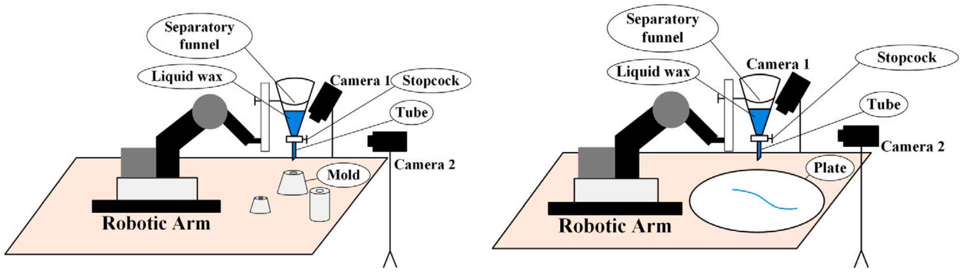
(1) In the aiming mode, children draw on the tablet to control the robotic arm to move the separatory funnel and align it with the mold they chose before. The real-time images captured by two cameras will help children to better aim at the target mold (See Fig. 6(a)). The robotic arm will follow the movement of the pen on the tablet. For example, if the user draws forward, the robotic arm moves forward. When the tube of the separatory funnel is aligned with the mold, liquid wax will be dropped into the mold by an assistant. When the wax is cooled off, the model will be retrieved.

(2) In the free mode, children draw their desired graphs on the tablet. The robotic arm moves by following the pen's trajectory. Unlike the aiming mode, an assistant will open the stopcock on the separatory funnel at the beginning of the drawing process to drop the wax on the plate. After cooling, a wax model the same as the drawing, is complete.

The original wax model may still have some flaws, so it is necessary to trim it until it meets the user's requirements.

Stage 2

The equipment used in Stage 2 includes a projector and a motion sensor (LeapMotion). The video clips are projected on the desk in front

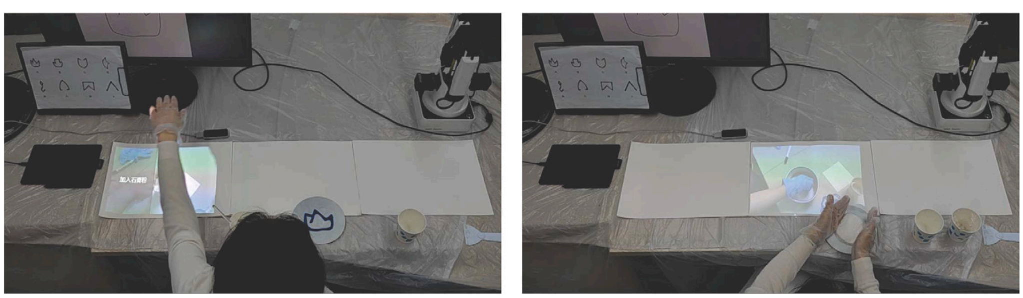


(a) Aiming mode (b) Free mode

Fig. 5. The area near the robotic arm in aiming mode and free mode respectively. (a) One or more molds are placed under the separatory tunnel in aiming mode. (b) A plate is placed under the separatory tunnel in free mode.

(a) Aiming mode (b) Free mode

Fig. 6. Photos of the aiming mode and free mode in Stage 1 of MakeBronze. (a) Children draw on the tablet to move the robotic arm to the mold. (b) Children draw their desired graphs on the tablet freely.



(a) Waving to switch the video clip (b) Covering the wax model with plaster instructed by the video clip

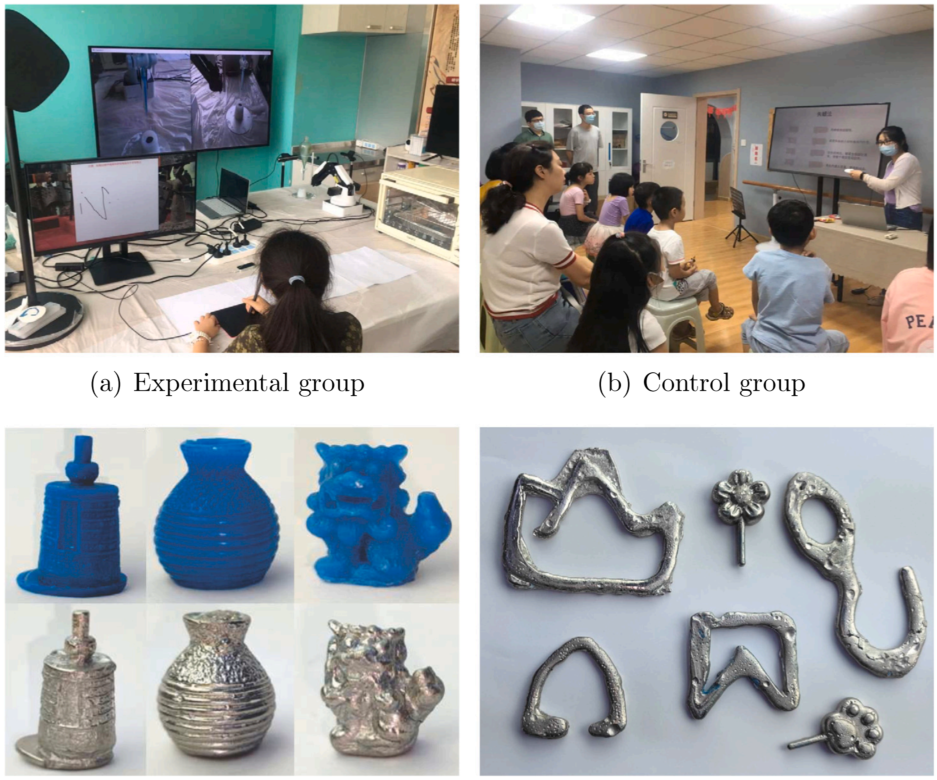
Fig. 7. In Stage 2, the video clips are projected on the desk in front of the children. (a) The User switches to the next video clip by waving their hands above the Leapmotion. (b) The user covers the wax model with plaster under the guidance of the video.

of the children (See Fig. 7). In this stage, the wax model will be covered by plaster and sent to an oven to bake until all the wax is melted. There are three video clips to teach children how to accomplish the task at this stage. Children will have the plaster on their hands during Stage 2, so it is necessary to use a gesture detector rather than other contact-type devices to switch videos. We used a LeapMotion to detect mid-air hand gestures for the children to advance the video. For example, waving at the LeapMotion camera switches the video to the next one (See Fig. 7(a)). The product of this stage is a hollow shell.

Stage 3

The operation of Stage 3 is similar to that of Stage 1. The main difference is that the liquid wax in the separatory funnel is replaced by liquid alloy with the help of an assistant. In this stage, the children need to align the tube of the separatory funnel with the hole (used to let wax out of the shell) on the plaster shell. Then, an assistant will help drop the liquid alloy. After the liquid metal solidifies, children will be taught to break the plaster shell with a hammer in order to obtain the metal model as the final product.

When interacting with our system, children used their visual, auditory, tactile, olfactory, and kinesthetic senses. The utilization of a robotic arm improves the safety of making wax molds, avoiding the risk of children being exposed to the high-temperature liquid during the process of making wax molds and providing the basis for the subsequent process of children's various tactile experiences based on wax molds (such as trimming them, covering them with plaster shells, cracking them) and the olfactory experience (the smell of wax when it melts). Moreover, children who have never used robotic arms before feel very novel and pay great attention to the movement of the robotic arm during the learning process. The movement of the robotic arms is consistent with the route drawn by children on the drawing tablet, which helps children have a better kinesthetic perception. The



(a) Experimental group (b) Control group

(c) Wax models and corresponding products (d) More products

Fig. 8. Photos of the user study. (a) Children in the experimental group used the MakeBronze system. (b) Children in the control group were given a 20-minute class. (c)Wax models and corresponding products. (d) More products made by children.

comprehensive design employed a multisensory approach to facilitate children's acquisition of knowledge regarding lost-wax casting.

5. User study

A user study was conducted in a Chinese school to evaluate if MakeBronze could help children better understand the lost-wax casting and increase their interest in bronze culture compared to the traditional learning method (attending class).

5.1. Participants

Sixty children were recruited to participate in the study, including 30 girls and 30 boys. They were screened to ensure that:

(1) Having normal or corrected-to-normal visual acuity, hearing, and no hand impairments of any kind;

(2) Not having any previous experience with the interactive system related to bronzes;

(3) Having no knowledge of lost-wax casting.

Participants were further divided into the experimental and control group, with an even distribution of age and gender. The participants in the experimental group aged between 7 and 14 years ($M = 9.86, SD = 2.21$), whereas those in the control group aged between 6 and 15 years ($M = 10.10, SD = 2.34$).

5.2. Experiment

We used a 2×2 mixed design with group as a between-subject variable, i.e., children in the experimental group used MakeBronze while those in the control group only attended a class about bronze culture (See Fig. 8).

Experimental Group

Children in the experimental group learned about lost-wax casting with MakeBronze. Before the formal experiment, the participants were presented with the history and inscriptions of Chinese bronzes briefly and given time to familiarize themselves with the operation of the drawing tablet. They were asked to learn eight simple inscription characters and write them correctly on the tablet. In this process, children used their auditory (listening to the researcher explain the task), visual, tactile (using the tablet), and kinesthetic (moving the hand to draw the inscription on the tablet) senses. Once we were certain they could use it properly, the formal experiment started. The whole experiment is divided into three stages corresponding to Section 4.2.

In stage 1, participants experienced the free mode and the aiming mode sequentially and made a wax model in each mode, respectively. Afterwards, they trimmed the wax models, which is crucial for getting a satisfactory product. This stage took about 5 min, excluding the time required for the wax to cool.

In Stage 2, the plaster powder and water were prepared for the participants in advance. Then they were asked to follow the instructions in three clips projected onto the desk sequentially: (1) Mixing the water and plaster powder to a pasty composition (Plaster); (2) Covering the wax model with plaster; (3) Placing the plastered wax model into an oven and waiting for all wax melted to get a plaster shell. LeapMotion was used to switch videos. Since the oven was turned on only after the plaster had been put in and the shell was only taken out after completely cooled down, children were not exposed to the high temperature. During this stage, we explained the materials used in ancient times and why we replaced the materials in our system (See Section 4.1.2). This stage took about 10 min, excluding the time spent waiting for all the wax melted in the oven.

In Stage 3, the separatory funnel with alloy liquid was fixed on the robotic arm in advance. Children moved the robotic arm to align the separatory funnel with the hollow shell. Once the correct position was reached (Directly above the hole of the shell), an assistant would help drop the liquid alloy into the plaster shell. When it cooled off, the plaster shell would be broken by children to get the final alloy product. Stage 3 took about 5 min, excluding the time spent waiting for the liquid metal to solidify.

During these processes, children used visual, auditory, tactile, kinesthetic, and olfactory senses. The visual senses were used throughout the learning process. The auditory senses were mainly used when the researcher gave instructions and when watching the instructional video in Stage 2. The tactile and kinesthetic senses were mainly used in the following steps: drawing on the tablet to control the robotic arm (Stages 1 and 3); mixing the water and plaster powder to a pasty composition (Plaster); covering the wax model with plaster; placing the plastered wax model into an oven; cracking the plaster shell. Children smelled the wax as it melted in the oven (Olfaction).

At the end of the experiment, children were asked to complete a questionnaire with four questions related to the lost-wax casting to assess their learning effectiveness. Furthermore, we conducted interviews with them in order to obtain feedback about the system.

Control Group

We provided the participants in the control group with a lesson about lost-wax casting to imitate the traditional learning method. The course duration was 20 min, which aligned with the prescribed length for the experimental group. The class mostly centered on lost-wax casting, with a brief introduction to the history and inscriptions of Chinese bronzes. At the end of the course, children completed the same questionnaire as the experimental group.

5.3. Result and analysis

5.3.1. Quantitative analysis

The results of the questionnaire indicated that the experimental group had a better comprehension of lost-wax casting in comparison to the control group. The questionnaire includes four questions about lost-wax casting:

SQ1: Which material is used for the model and which material is used for the shell in Chinese traditional lost-wax casting?

SQ2. What characteristics should the material for the model have?

SQ3. What characteristics should the material for the shell have?

SQ4. Sort the steps of lost-wax casting.

These four questions correspond to the different key issues associated with the lost-wax casting. The question *SQ1* was used to evaluate participants' familiarity with this traditional casting method by asking them about the materials used in the Chinese traditional lost-wax casting. Subsequently, the question *SQ2* and *SQ3* were employed to assess participants' comprehension of the principles of the lost-wax process by testing their understanding of the characteristics of the raw materials, such as the disparity in melting points between models and shells. Lastly, the question *SQ4* was utilized to ascertain participants' comprehension of the workflow.

We calculated the questionnaire scores as well as the accuracy for each question for both groups and analyzed the data between experimental and control groups using the independent-samples T-test.

The average score of participants in the experimental group was 88.33, with a standard deviation of 17.03. In comparison, the average score of participants in the control group was 65.83, with a standard deviation of 24.98. There was a significant difference between the two groups ($t = 4.08, p < 0.001$). The result revealed that in comparison to learning in class, using the MakeBronze system enabled children better comprehend how the lost-wax method works. This is probably due to the fact that novel technologies are attractive to children (Gooch et al., 2016) and the hands-on process helps them better engage in the learning process (Price et al., 2017; Jewitt et al., 2021), which in turn helps them better understand and remember relevant knowledge.

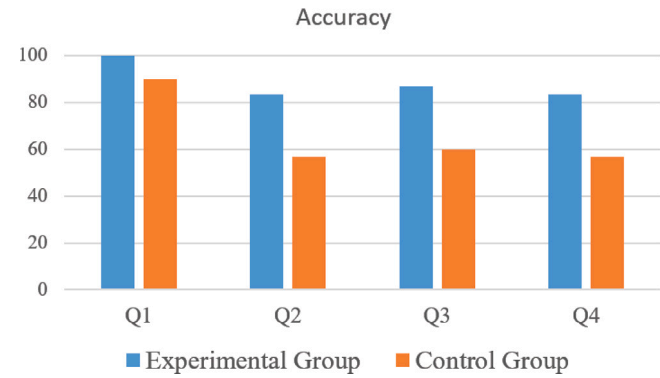


Fig. 9. The accuracy of the experimental group is higher than that of the control group for all questions in the questionnaire.

The accuracy of each question was calculated and displayed in Fig. 9. For *SQ1*, the accuracy of the experimental group was 100.00% and that of the control group was 90.00%. The result of independent T-test showed that there was no significant difference between the two groups ($t = 1.80, p = 0.08$). This may be due to the fact that the question *SQ1* only requires a simple memorization of what raw materials are used in the traditional Chinese lost-wax casting, which is not difficult for the children. For *SQ2*, the experimental group had a higher accuracy of 83.34% compared to the control group's accuracy of 56.67%. A notable distinction was observed between the two groups ($t = 2.32, p = 0.02 < 0.05$). For *SQ3*, it was found that the experimental group had an accuracy of 86.67%. In the control group, the accuracy was only 60.00%. A significant distinction was also observed between the two groups ($t = 2.41, p = 0.02 < 0.05$). These two questions asked the children about the properties that the raw materials that can be used in the lost-wax casting should have, which is closely related to the principle of lost-wax casting. The model needs to be made of a material that melts easily, and the material of the shell should be able to resist high temperatures. In this way, when the model is melted in a high-temperature environment, the inside of the shell has a cavity with the same shape as that of the model. In addition, the material used to make the model also needs to be easy to carve in order to finally create a sophisticated product. The results suggested that participants of the experimental group had a better comprehension of the fundamental principle of the lost-wax casting. In Q4, the accuracy for the experimental group was 83.34%, whereas the control group's accuracy was 56.67%. Between the two groups, there was a significant difference ($t = 2.32, p = 0.02 < 0.5$). It could be the consequence of the children's improved memorization of the lost-wax casting procedure due to the hands-on approach.

5.3.2. Qualitative analysis

In order to get the participants' opinions on MakeBronze, we asked the following five open-ended questions during the interview:

PQ1. Which was the most interesting part of the entire process?

PQ2. Which was the least interesting part of the entire process?

PQ3. Which was the most challenging part of the entire process?

PQ4. How do you feel about the system? For example, was it easy to use, were the instructions easy to understand?

PQ5. Did this system increase your interest in learning about bronze culture?

PQ6. How could the system be improved?

In-depth interviews and systematic analysis were conducted for qualitative analysis. From their feedback, the general attitude was positive, but we observed some differences in children of different ages.

(1) **The most interesting part.** 17 children (56.6%) chose the process of utilizing the drawing tablet to control the robotic arm as the most interesting part. They said that they had never operated the

robotic arm with a tablet before, and it was a very novel experience for them. Nine kids (30%) said that breaking plaster shells to get the final products was the most intriguing part, indicating that they were delighted with the physical products of their labor. This is the advantage of our system to get a physical product, while other bronze-related interaction systems tend to focus only on the interaction and presentation of the virtual 3D models.

(2) **The least interesting part.** 12 children (40%) highly appraised MakeBronze by expressing that there was no tedious part of the whole system, and the remaining 18 children reported what the least interesting part they thought was. 12 children (66.7%) voted for the process of waiting for the wax model to melt, and hoped that it would be accelerated. In fact, for the safety of the children, it does take more time to let them take the shells out of the oven only when they are completely cooled. The results also revealed that the older children had a higher demand for the adequacy of tasks in the teaching process, and they were more likely to lose patience during idle time without tasks than the younger children.

(3) **The most challenging part.** 19 children reported what they felt was the most challenging part. "*I had never used a tablet before, but I found it very similar to my usual drawing process, so I quickly became familiar with its operation.*" 10 of them said they found it difficult at the beginning to use the drawing tablet because they had no previous experience with it, and that is why we give them some time, which usually did not take long, to get familiar with the operation of the tablet before the formal experiment. Five children thought covering the wax model with plaster was a great challenge for them, because the plaster shell was easy to break before it was thoroughly dried. Four children expressed their safety concerns. They felt unsafe while breaking the shell with a hammer or trimming the wax model with a knife, but they also believed that being careful or seeing the tips in advance would be helpful. The reason is that their strength is limited, but we chose the usual size hammer, which may be too heavy for them, so as to make them feel risky. Therefore, we will choose tools suitable for younger children to reduce the risk subsequently.

(4) **Feelings.** All of the children expressed their strong desire to experience it again to make more products, e.g., "*Could I make another product, please? I want to make a flower for mom.*" They felt that both modes had their own advantages, with the aiming mode allowing for a more stereoscopic and elaborate model with the help of silicone molds, and the free mode offering greater flexibility. 26 children (86.7%) thought MakeBronze was very easy to use, and the reason may be that we chose the drawing tablet as the interface, and its operation is very similar to the usual process of drawing on paper. 26 children (86.7%) thought the instructions of our system were quite easy to understand. The most likely reason is that instructions of Stage 2 were displayed in video clips, which are easy to follow. Moreover, the operations of Stage 1 and Stage 3 were similar, reducing the difficulty of operating the robotic arm for children.

(5) **Effectiveness.** When asked if they would like to experience other bronze-related interactive systems, all of the children (100%) said they were willing to. 26 children (86.7%) showed a heightened interest in bronze culture. They expressed their increased interest in bronze culture directly and revealed which aspects of the bronze culture they would like to learn more about, and gave their next learning plans, such as asking their parents to obtain more bronze-related books or going to museums. Although the improvement of interests requires a long-term observation, this result also shows the great potential of our system to increase their interest in the bronze culture.

(6) **Valuable suggestions.** Children also gave their valuable suggestions. For example, they expected that the tablet's reaction time and precision could be increased. One child acknowledged that she could not pay attention to screen 1 when drawing on the tablet, and she said, "*I think it would be better if I could draw directly on the touch screen and display the path in real-time.*" This is a good suggestion for our system, more intuitive and space-saving. Three children said they wanted to utilize the robotic arm for further tasks, like breaking the plaster shell, thus making the system security to be enhanced, e.g., "*I hope that the process of breaking the shell can also be completed by the robotic arm, so it will be safer.*"

6. Discussion

The result in Section 5.3.1 indicated that the MakeBronze system is more effective in helping children understand the process of the lost-wax method than the traditional approach, as reflected by higher accuracy in the test. The results of the interviews in Section 5.3.2 showed that children gave a very positive evaluation as a novel way of learning that would increase their enthusiasm for learning about bronze culture, and that it was a successful attempt to publicize traditional culture by using an interactive system designed to be easy for children to operate. It also brings some specific knowledge for children, for example, learning some characters of inscriptions during the writing process (Chinese traditional culture) and a practical feeling of low melting point and softness of wax during the mold-making process (Physical properties of materials).

There are many opportunities to use interactive systems to assist children with multisensory learning. Most of the existing multisensory learning systems for children are based on virtual scenarios, which mainly use the child's sense of sight and hearing, and use touch screens or controllers to help the child with tactile input. However, our system imitates the traditional bronze casting method to produce tangible products, and the process will also be in contact with the tangible materials, so the tactile and kinesthetic experience will be better than just tapping the screen or manipulating the controller. The subsequent design can also enhance the tactile, kinesthetic, and olfactory experience of children by using child-friendly technology. When completing relatively complex tasks, there are challenges in the child's perceptual integration process. For example, when writing on the drawing tablet to control the robotic arm, the child needs to simultaneously watch the screen and draw on the tablet, while maintaining a constant speed so that the thickness of the wax mold is uniform, which may be difficult for younger children.

Moreover, unlike other bronze-related interactive systems that focus on the display of 3D virtual models, our system is a good simulation of the casting process of bronzes. It reproduced lost-wax casting safely, and the physical product is available for children to observe and touch.

The system was created, and the components and materials were selected based on the children's characteristics and the purpose of the research. For example, the primary purpose of this work is to publicize bronze culture and enhance children's interest in learning. In order to reduce the difficulty of popularizing the system, we should choose equipment that is familiar to children and easy to purchase.

In the user study, we also found that children of different ages showed some differences when using our system, **offering some insights into the design of child-oriented interactive systems.**

(1) *The questionnaire and instructions must be very easy to understand*. We discovered that younger children, perhaps due to their small vocabulary, sometimes did not understand the questionnaire and required an adult to explain it. Naturally, we took particular care during the explanation process to avoid giving away the answers. Therefore, surveys or tasks designed for children need to be as simple and easy to understand as possible to reduce their difficulty in comprehension and to get more accurate feedback.

(2) *It is preferable to design tasks according to children's age*. It investigated that younger children generally have less strength than older ones, so it would be better to choose suitable tools for them. Moreover, it may be beneficial to provide some time for them to rest during the experiment. For older children, it is important to consider the adequacy of their tasks when using the system. They have less tolerance for idle time than younger children, so it is necessary to consider occupying them to avoid boredom.

(3) *The interaction should be as simple as possible or similar to what children often do*. For example, waving to control LeapMotion, or using a tablet that is similar to their daily drawing process on paper, can well reduce their learning burden and make the interaction process more natural.

(4) *The operation needs to be flexible*. According to our study, children liked the flexible design of the system, such as when to move to the next video during Stage 2, depending on their progress in completing the task. Additionally, they also appreciated the free mode in Stage 1, which allows them to customize the model as they like.

In addition, **our study demonstrates the feasibility of using interactive tools to publicize traditional culture to children**, broadens the application scope of HCI, and the research approach can be transferred to other works in the future. That is, enhancing children's interest and making it possible for them to learn about the fabrication of traditional crafts by employing tools that are easily accessible to children, replacing raw materials that may bring risks, and decreasing operational obstacles.

7. Limitation & future work

There are some limitations in MakeBronze. Firstly, an assistant is needed to control whether the liquid in the separatory funnel drips. Although the efficiency of our system is not affected, adding a stopcock control mechanism to automate MakeBronze is required. Secondly, the color of the final product is different from that of real bronze. Actually, real bronzes are golden, and the green color children see in books, movies, or museums is caused by patina. In order to improve children's experience, we can provide some pigments for them to dye the final product or find some alloys with closer colors of bronze. Thirdly, aligning the robotic arm to the target under the guidance of the images taken by cameras is a challenging task for some children. There is a lack of intuitive instruction on the screen, and we will explore ways (e.g., using symbols) to help children complete the alignment process more efficiently. Moreover, we will consider designing some extra educational tasks to occupy the children, making the process of waiting for the wax to melt less tedious. From a system design perspective, we did not involve children in the design process of MakeBronze, but only provided some design guidance for subsequent child-oriented learning systems according to their feedback. Inspired by Druin (Druin et al., 2009), McNally (McNally et al., 2018) and Benton (Benton et al., 2014, 2012), engaging children in design offers some potential benefits. Therefore, In the subsequent design of a child-oriented multisensory learning system, we will take this approach and improve the system in accordance with the child's suggestions.

8. Conclusion

Chinese bronze is a representative cultural heritage with high aesthetic and historical value. To publicize its culture, we present an interactive system called MakeBronze for children to learn and experience the process of making bronzes and create their own artifacts safely by following the traditional approach in ancient China. Our system was developed to fill the gap in the existing methods of dissemination using paper, videos, and exhibitions by providing children with a hands-on experience to interact with bronzes while learning the bronze culture. Through a user study with 60 children, we showed that children were more engaged in learning with our system in comparison to the traditional learning method. Children could also understand the fabrication process of Chinese bronze better by using our system. We believe our work has great potential as a dissemination tool to increase children's interest in the bronze culture. The success of MakeBronze provides more possibilities to preserve cultural heritage with modern interactive technology. Moreover, some valuable suggestions on the design of interactive systems for children were obtained, which will be of great help in designing subsequent child-oriented interactive systems.

CRediT authorship contribution statement

Minjing Yu: Conceptualization, Methodology, Visualization, Formal analysis, Writing – original draft, Writing – review & editing. **Li Wang:** Software, Visualization, Writing – review & editing. **Mingxu Cai:** Investigation, Data curation, Writing – review & editing. **Mengrui Zhang:** Investigation, Validation. **Chun Yu:** Methodology, Writing – review & editing. **Xing-Dong Yang:** Methodology, Writing – review & editing. **Jiawan Zhang:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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