4Doodle: 4D Printing Artifacts Without 3D Printers

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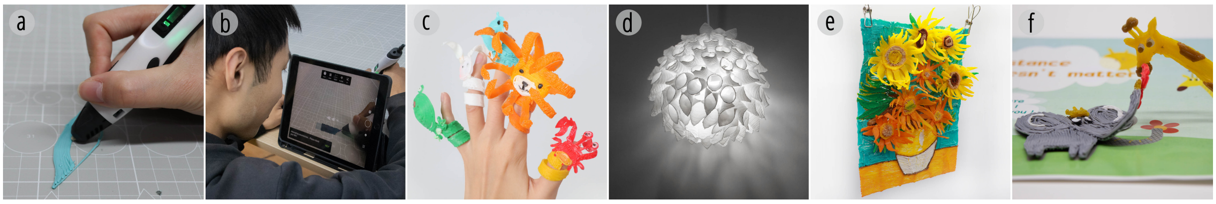

Figure 1: 4Doodle comprises a handcrafting 4D printing approach and (a, b) a mixed-reality-guided design tool to help novice users practice and master the manual skills of 4D printing using a 3D pen. Diverse 4D artifacts can be created with fully human intervention; e.g., (c) animal covers can be customized by self-spinning to fit fingers; (d) modular self-folding cannoli shapes can be reassembled into a lampshade; (e) artistic representations of flowers can be made to "bloom" with heat triggering; (f) transformations can enhance storybook interactivity while storytelling.

ABSTRACT

4D printing encodes transformability over time, which empowers users to create artifacts by on-demand deformation. The creative process of 4D printing shape-changing artifacts can be challenging because of its discontinuous fabrication steps, such as digital designing, specific path planning, automatic printing and manual triggering. We hypothesize that switching from typical 4D printing reliant on 3D printers to a more "handcrafted" method can allow users to understand and continuously reflect upon the artifact and its transformability. Towards this vision, we introduce 4Doodle, a hybrid craft approach that integrates unique deformation controllability and five techniques for freehand 4D printing, using a 3D pen. To tackle the shape-changing challenges of uncertain hands-on fabrication, we develop a mixed reality system to help novices master the manual skills of 4D printing. We also demonstrate a series of 4D printed artifacts with fully human intervention. Finally, our user study shows that 4Doodle lowers the skill-acquisition barrier associated with handcrafting 4D printed artifacts, and it has great potential for creative production and spatial ability.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**;

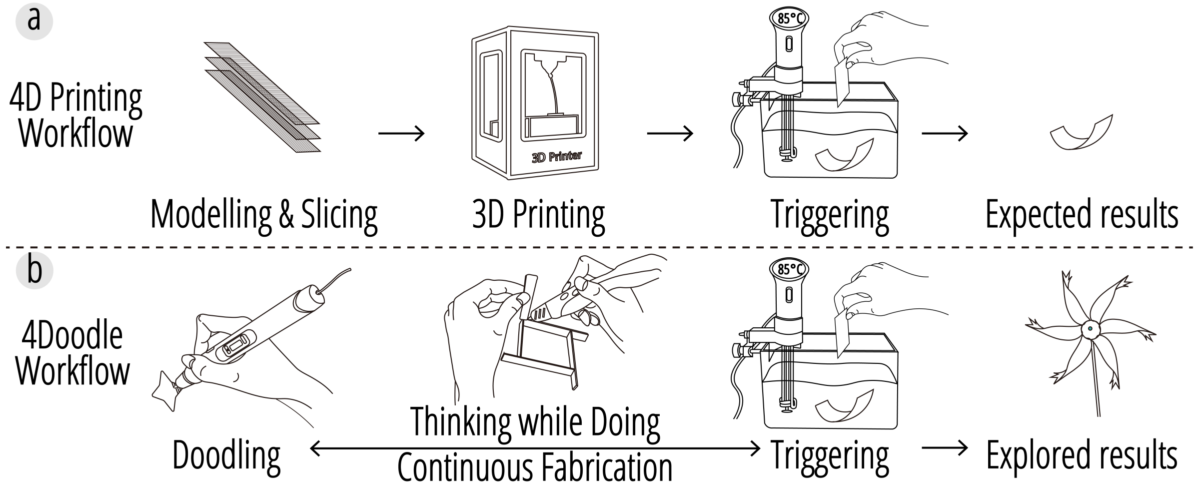

Figure 2: 4Doodle allows users to morph components into explored results from a continuous fabrication perspective.

KEYWORDS

4D printing, 3D pens, Shape-changing behavior, Hybrid craft

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1 INTRODUCTION

4D printing encodes an extra dimension of transformation over time, which empowers users to create artifacts with complex geometric dimensions (e.g., origami-shaped [1], line-shaped [44] or non-developable shapes [12, 45]), diverse composite materials [37, 43] or easy post-print modifications [18]. However, 4D printing to create artifacts is challenging when a typical fabrication process is being conducted (Figure 2a): users design a simple "flat" model digitally, preview what transformations it is capable of and make alterations until a satisfactory design is obtained; this can then be fabricated automatically by a 3D printer and the physical pieces heat triggered to complete the deformation. For example, Thermorph [1] and A-line [44] provide users with advanced design tools to help them participate in the design process of 4D printing and improve the predictability of design results. Users can obtain the expected results without having to understand the deformation principle or participate in the fabrication process. In the following works, TF-Cells [18] provide an internal structure for 3D printing objects, enabling users to modify a certain range, and Fab4D [9] utilizes heat triggering methods to enable non-experts to hybrid-craft shape-changing artifacts, which can enhance user participation in the post-printing stage. In the above systems, users participate in a single stage to design and fabricate 4D artifacts. However, the discontinuity between design and fabrication, the digital and physical world and human-machine interaction thereby prevents users from having full control over physical matter [2].

Traditional craft techniques often involve manual manipulation or transformation of materials and production of handmade artifacts in an instantaneous and continuous manner [32]. We therefore hypothesize that switching from typical 4D printing reliant on 3D printers to a hands-on method can enable users to understand and continuously reflect upon the artifact and its transformability (Figure 2b).

Most recent Human-Computer Interaction (HCI) research on hybrid crafting has focused on assisting users by lowering the learning barrier of formal knowledge in specific domains [8, 10, 48, 49]. In particular, hybrid 4D printing has been demonstrated, applied to the manual trigger process [7, 9]. However, human intervention in 3D printing of deformed artifacts has not been fully explored.

The previous work [53] and our pilot study have shown that it is challenging to actuate suitable deformation behavior because of the uncertainty associated with speed control in manual printing, especially for novice users.

In this paper, we investigated the unique controllability of shape-changing and five hands-on techniques for supporting deformation behavior, using an off-the-shelf 3D pen. This technique, called 4Doodle, facilitates low-cost 4D printing and can open up new design spaces, such as printing on arbitrary shapes for inverse transformation or allowing assembly in different stages to achieve complex structures. Although it is difficult to achieve high-accuracy advantages over conventional 4D printing reliant on 3D printers, we believe that 4Doodle can open up a new research avenue for reversible 4D printing and provide more creative techniques for makers and STEM educational courses.

Our key contributions are threefold:

- Identifying and implementing the key factor of deformation behavior in hands-on 3D printing, through a pilot study and a series of experiments using 3D pens. We converted a typical

4D printing mechanism created by standard 3D printers to facilitate doodling and to democratize the technology and facilitate human intervention.

- Building a mixed reality (MR) system, serving as an educational tool to enable novice users to learn the requisite skills and perform design previewing. The system allows users to print simple shapes using the techniques that we developed, which can serve as scaffolding for skill learning.
- Conducting wide-application cases and a user study, showing the potential to use the 4Doodle method in creative deformation. The results of the user study verified that our 4Doodle method lowers the skill-acquisition barrier associated with hands-on 4D printing, and has great potential in terms of creative production and spatial ability.

2 RELATED WORKS

2.1 Personal Fabrication with a Handicraft Approach

Digital fabrication tools have widened the scope for personal fabrication [2, 23] and have popularized design technology and significantly lowered the skill threshold for using both hardware and software, promoting accessibility for inexperienced users [3–5, 16, 24, 25, 39, 50]. Recent works have developed handheld tools to support the handicraft approach, with consideration of human factors in the fabrication process. For example, in the 3D Pen + 3D Printer study [38], the role of humans and fabrication machines was explored through a new process of 3D modelling with 3D pens and 3D printers. FreeD [49] is a handheld digital milling device guided and monitored by computer while preserving users' freedom to sculpt and carve. D-Coil [27], Mixed Dimensions [13] and Desktop Electrospinning [31] are shape-painting tools for wax-like materials as well as molten polymer. Other developments such as BodyStylus [29] and Aesthetic Electronics [20] include handheld tools to assist in creating circuits on skin, paper and fabric. Inspired by these innovations, we adapted the hybrid fabrication concept to explore the possibility of manually printing morphable materials.

2.2 Computational Tools for Hybrid Fabrication

The computational tool serves as a bridge to combine digital fabrication and personal crafting [14, 15, 17, 21, 51, 52]. Researchers have demonstrated plenty of computational software platforms and systems to improve hands-on experiences, especially for novice users. For example, Adroid [40] helps users control a robotic arm to use handheld tools with precision and accuracy, according to applied forces. Turn-by-Wire [41] combines traditional lathe functions with haptic input controllers for a more fluid making process. Other systems provide spatial cues by displaying technologies such as augmented reality (AR) and mixed reality (MR) [28, 33]. WireRoom [47] has a computational framework that generates 3D wire shapes from given 3D models, and Just Draw It [11] is a method for creating 3D curve network models. Wiredraw [48] is an MR system that can offer 3D drawing guidance for immersive wire sculpturing with a 3D pen, while RoMA [26] uses an AR device to provide virtual fabrication operations and a display enabling the designer to integrate real-world constraints into a design intuitively. Interactive fabrication [54] comprises a series of prototype devices that use real-time input to fabricate physical form, illustrating the potential of interactive fabrication. In general, these tools help lower the fabrication skill barrier, improve precision and promote efficiency, thus promoting accessibility, even for users without prior experience.

2.3 4D Printed Shape-Changing Artifacts

4D printing based on thermoplastic materials can fabricate three-dimensional shapes morphing out of linear or simple two-dimensional elements [19, 22, 30]. Researchers in the HCI community have proposed various methods and systems to facilitate creative making using 4D printing techniques. A-line [44] is a method to fabricate morphable linear structures. Printed Paper Actuator [42] can print conductive PLA material on paper to achieve electrical actuation and sensing of a curved paper surface. Thermorph [1] features an origami design algorithm that can produce self-foldable, flat thermoplastic composites. Geodesy [12] is a 4D printing process to design and fabricate continuous double-curvature surfaces or surface textures, and 4DTexture [36] focuses on deformable 3D surfaces with texture. 4DMesh [45] and SimuLearn [46] are data-driven methods that help users efficiently create functional morphed grids on a larger spatial scale.

However, most of the 4D printing developments described above require highly automated 3D printers as fabrication devices, and the human aspect of the fabrication process is rarely discussed. Recently, a few works have started to consider user participation in post-processes. For example, Ko et al. [18] presented a metamaterial structure called thermoformable cells, enabling users to modify the shapes of 3D printed objects easily. In the Fab4D study [9], heat triggering methods were investigated to enable non-experts to create shape-changing behaviors. Multifunctional mesostructures [6] are 4D printed functionally graded structures inspired by natural materials. "Unmaking" [34] entails production of printed models as a way for designers to realize the artistic value of destruction. In the field of material science, Song et al. [35] developed a technology that can directly transform pen-drawn 2D precursors into 3D geometries with specific lab materials. These works clearly demonstrate the role of human intervention in the design and fabrication process and the need for research into the potential of 4D printed shape-changing interfaces in the HCI area.

Previously, 4D doodling [53] has preliminarily verified the feasibility of hands-on 4D printing to create self-bending decorations. However, effective controllability and reliable deformation output have not been provided. In this paper, we will demonstrate the controllability of hands-on printing and present five hands-on techniques facilitating complex deformation, using software developed to help users practice 4D printing skills, which can help democratize 4D printing from the realm of research into makerspaces and craft education.

3 OVERVIEW OF 4DOODLE

The key to successful hands-on 4D printing is understanding the deformation mechanism and key factors that affect deformation, and being able to effectively master the control skills. In this regard, we transform complex scientific knowledge into visual guidance to help users quickly master 4D printing. As shown in Figure 3a, we divide the key deformation factors into printing direction, printing

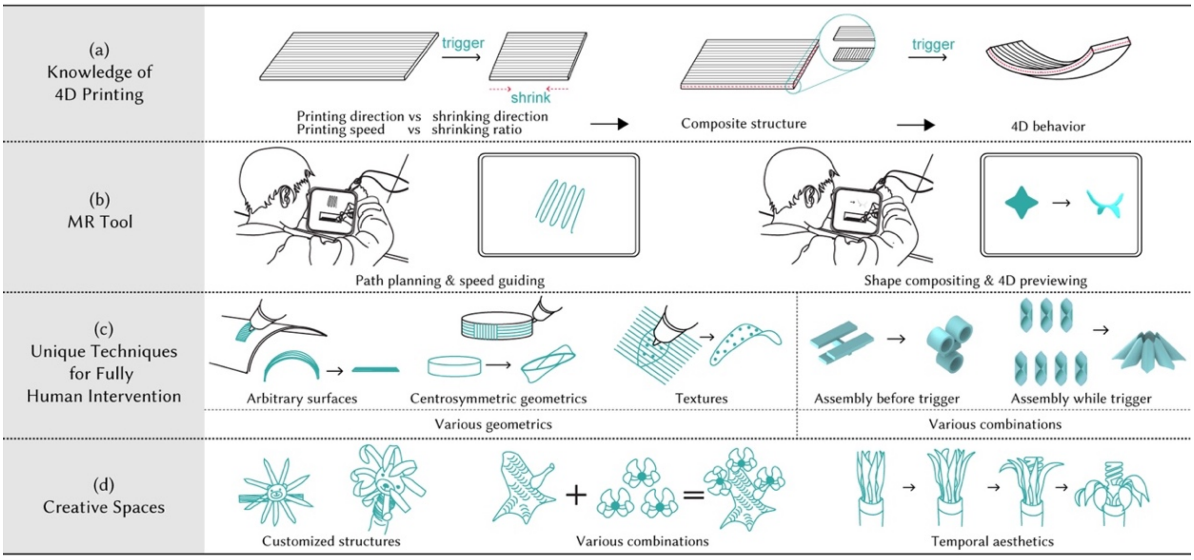

Figure 3: Using 4Doodle, users can (a) understand the principle of 4D printing, (b) practice via the MR-guided tool, (c) explore the principle using five techniques with fully human intervention, and finally (d) create their 4D artifacts.

speed and composite structure, which affect the shrinkage direction, shrinkage rate and deformation behavior, respectively. Based on the above principles, 4D deformation behavior can be produced by composite structural design.

To help users master 4D printing faster, our method uses a digital tool (Figure 3b) to achieve two design goals: (1) printing path planning and printing speed visualizing to guide manual printing and achieve the deformable standard; (2) composite structure setting and deformation simulation to help users recognize the deformation target, allowing users to imagine the shape-changing more intuitively.

Once have mastered the basic skills, users can learn and freely use the five unique manual skills (Figure 3c) we explored to fully participate in 4D creation. We envision using 4Doodle to get people involved in enriching handicrafts with customized structures, expanding handicrafts with various combinations, and creating handicrafts with temporal aesthetics (Figure 3d).

4 PILOT STUDY: 4DOODLE CHALLENGES AND OPPORTUNITIES

We conducted a pilot study to see how well users can learn manual 4D printing. We also sought to identify the differences between manual 4D printing and 4D printing by machines, and determine the opportunities presented by 4Doodle. We recruited four casual users and explained how to use the 3D pens. We prepared 4D printing works [1, 12, 44] and a 4D printing video as learning tutorials. Users were also allowed to search for other related learning tutorials online.

We gave users a live demonstration of how to 4Doodle and asked them to imitate it. However, they were not able to obtain

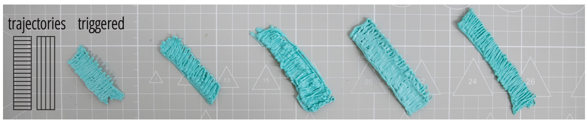

Figure 4: The initial prints did not show a dramatic shape-changing effect with a bi-layer composite, which is generally used for the self-bending structure.

satisfying results from hand-drawing samples. As shown in Figure 4, the expected bending of the bi-layer structures (actuator layer and constraint layer [1], which are key to deformation) was not achieved after hot water triggering. Having analyzed the performance of a skilled person, we found that the reason for this was that layer thickness and printing speed (which are two key factors in 4D printing) could not be mastered effectively during manual printing. The participants' feedback was summarized as follows:

- Intuitive ways to understand and experience 4D printing are needed. One user said that reading professional papers is difficult and a little boring.
- The 3D pens can lower the barrier to engagement in the 3D experience. One participant said that she did not have any prior 3D printing experience, and it was hard for her to understand what "slice" meant but she can understand drawing easily.
- Watching videos was not sufficient to enable users to effectively master the relation between printing speed and the degree of deformation.
- To conclude, a handheld printing device brings both challenges and opportunities to the fabrication process.

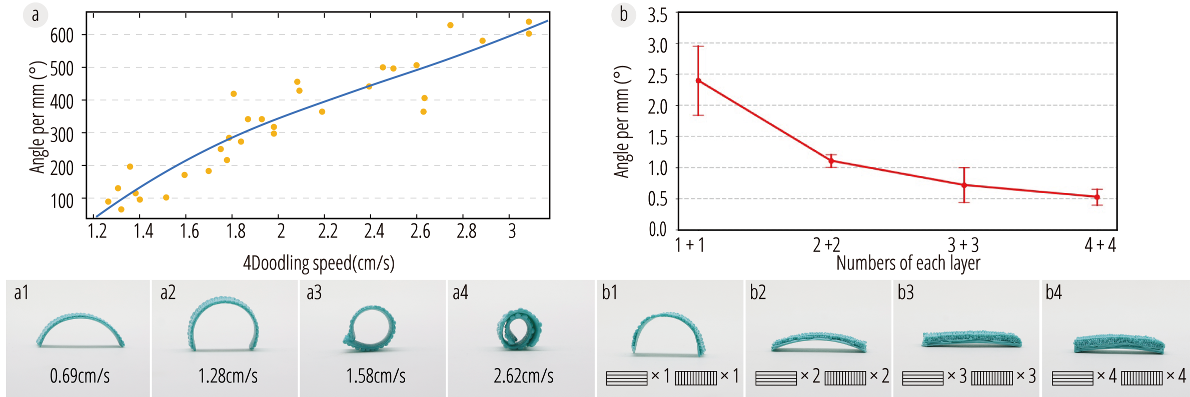

Figure 5: The quantitative analysis of the bending performance based on the controllability of (a) the printing speed and (b) the thickness of the sample.

- The pilot study enabled us to formulate design goals for the purpose of providing a user-friendly tool for our 4Doodle method, as follows:
- The system should assist novices with basic 4Doodle techniques. In particular, it needs to teach users how to print 4Doodling trajectories at a proper 4Doodling speed, which influences the deformation result.
- It should provide for multi-segment design and transformation previewing for practicians to understand the relation between trajectories, speed and deformation.
- It should be implemented in a convenient and comfortable manner. Considering the operational load issues on the heavy head-mounted display and the fact that images from the projector could be obscured by the hands, we finally chose an iPad for its accessibility and portability.
- To maximize crafting creativity, we wanted to include expansive doodling techniques to enhance the 4Doodling experience beyond the conventional 4D printing by machine. The system needed to teach users and freely use these expansive manual techniques.

5 EXPERIMENTS ON CONTROLLABILITY

5.1 Shape-Changing Mechanism Using a 3D Pen

In this section, we describe how we addressed the aforementioned challenges, tested the unique conditions of manual 4D printing and made preparations for our software, supporting our unique mechanism to enable a hand-drawn piece to possess a dramatic shape-changing property.

5.1.1 Experimental Setup. All the samples were printed by an off-the-shelf 3D printing pen (SUNLU SL-300), with an extrusion temperature of 170°C, using Polymaker PolyMax PLA filaments with a diameter of 1.75 mm. The spinning speed was about 0.687 cm/s. The printing needed to be attached on a relatively frictional yet non-stick surface, such as blue tapes used in 3D printers and cutting mats. The experimental ambient temperature was 20°C–30°C, and the relative humidity was 30%–60%. All the samples were 50 mm in length and 10 mm in width and were later triggered in hot water (85°C) for uniform heating to improve data accuracy. The results were reported as average data with an error bar for at least four repeated experiments.

5.1.2 Doodling Speed Vs. Bending Angle. The printing speed is an effective control parameter to determine the maximum bending angle. We synthesized a function from the relation between doodling speed and deformation (Figure 5a). At a 95% confidence interval, the expression of the bending angle (denoted as a) as a function of the printing speed (denoted as v) is $a = 559.5ln(v) + 4.534v - 61.3$, where the residual sum of squares is $1.027e + 5$, and the coefficient of determination is 0.8821.

5.1.3 Thickness Vs. Bending Angle. Although it is difficult to control the layer thickness when hand doodling, the overall thickness of the sample is also a factor that affects the deformation process. We investigated different dimensions of the bi-layer ratio from a 1 x 1 layer to 4 x 4. Figure 5b illustrates that the thinner the sample is, the bigger the bending angle will be.

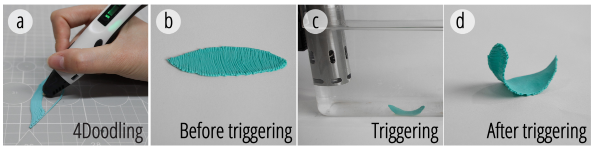

Figure 6: The basic workflow of hands-on fabrication: (a) doodling on a cutting mat to create (b) an initial flat piece, which can (c) be triggered in hot water to (d) complete the transformation.

5.2 Basic Hands-On Workflow

Based on parametric experiments, we summarized a basic workflow for 4Doodle: users can doodle an expected 2D shape on a cutting mat using a 3D printing pen, with an appropriate doodling speed and a reasonable number of layers (Figure 6a); after doodling, users can produce the initial shape, which is usually flat with a bi-layer structure (Figure 6b); the initial shape can be triggered in hot water (Figure 6c) or by other heating methods, such as a heat gun; after triggering, an unexpected but reasonable 3D shape can be obtained (Figure 6d). In addition, we reproduced several classic shape-changing structures of conventional 4D printing works to verify the availability of 4Doodle, for example, the helix in A-line [44], the twist in MorphingCircuit [43] and the wave structure in Thermorph [1].

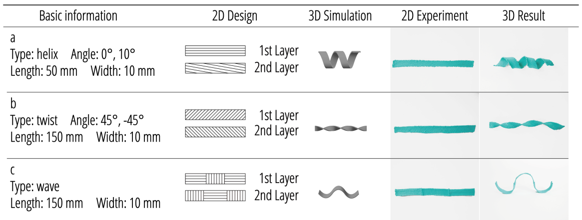

Figure 7: The classic structures of conventional 4D printing can be reproduced by 4Doodle, such as the (a) helix [44], (b) twist [43] and (c) wave [1] structures.

5.3 Five Expansive Techniques in Hands-On Fabrication

4Doodle does more than simply facilitate 4D printing by machine. Creativity is enhanced with 4Doodling by a free 3D pen, so there is more manual control, enabling users to have a more tactile experience and inspiring them to experiment while creating. We want users to feel this novel deformation crafting and create beauty during the process. After summarizing the expansive 4Doodle deformation techniques, we added them to our MR system. If users have good control of these techniques after learning via the MR system, they can then freely 4Doodle.

5.3.1 Printing on Arbitrary Surfaces for a Reverse Transformation. In contrast to printing on the flat platform using 3D printers, users can 4Doodle on everyday objects which have arbitrary surfaces in order to obtain various original shapes and see how these surfaces can morph. As a 3D pen is highly flexible, users can draw on the ridge of a bent cutting mat, producing an arc that can transform into a flat sheet after triggering, as shown in Figure 8. This technique can achieve a reverse transformation which is difficult for conventional 4D printing by machine.

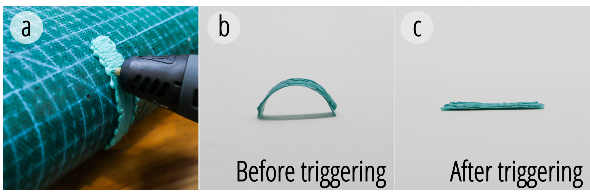

Figure 8: (a) Printing on arbitrary surfaces can achieve a reverse transformation from (b) a curved piece to (c) a flat piece.

5.3.2 Printing Centrosymmetric Geometric Shapes Using a Turntable. Curved and centrosymmetric figures can easily be printed by 3D printers, but drawing them by hand is challenging because of their stringent requirements in terms of geometry and size. Inspired by ceramic crafting, we employ a turntable that can rotate at a constant speed and be used to design centrosymmetric molds, allowing users to manipulate the printing pen while the turntable is in a static position, to obtain a centrosymmetric three-dimensional shape (Figure 9). The final shape is determined by encoding different shrinkage ratios radially on a circular disk. Similarly, users can draw around a cone made of paper with different traces and constraints. Notably, to increase adhesion, the paper substrate is wrapped in a layer of tape.

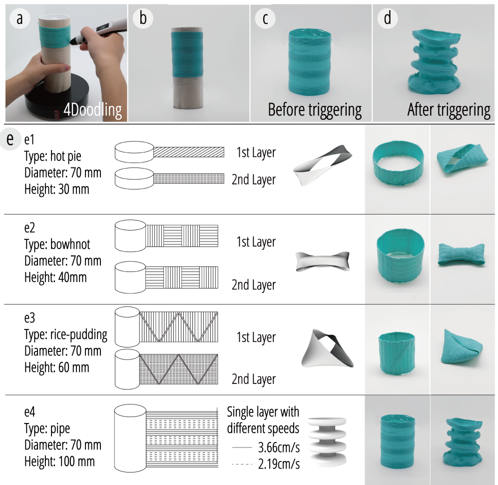

Figure 9: Users can (a) 4Doodle onto a static surface to (b) produce a centrosymmetric geometric mold, which can achieve a transformation in (c) three-dimensional space.

5.3.3 Printing Textures Enriching Haptic Aesthetics. Texture is an integral part of handicrafts and plays an important role in human tactile perception. 4Doodle provides a way to freely draw textures similar to oil brush strokes on 3D surfaces. Based on the bi-layer composite structure we experimented with (Figure 10), users can doodle arbitrary textures (e.g., waves, polylines, dots, etc.) as a constraint layer to design unique decoration on 3D surfaces.

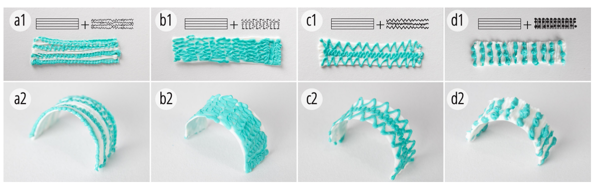

Figure 10: The triggered surfaces with different textures, i.e., (a) short waves in lines, (b) crossed waves, (c) polylines and (d) dots.

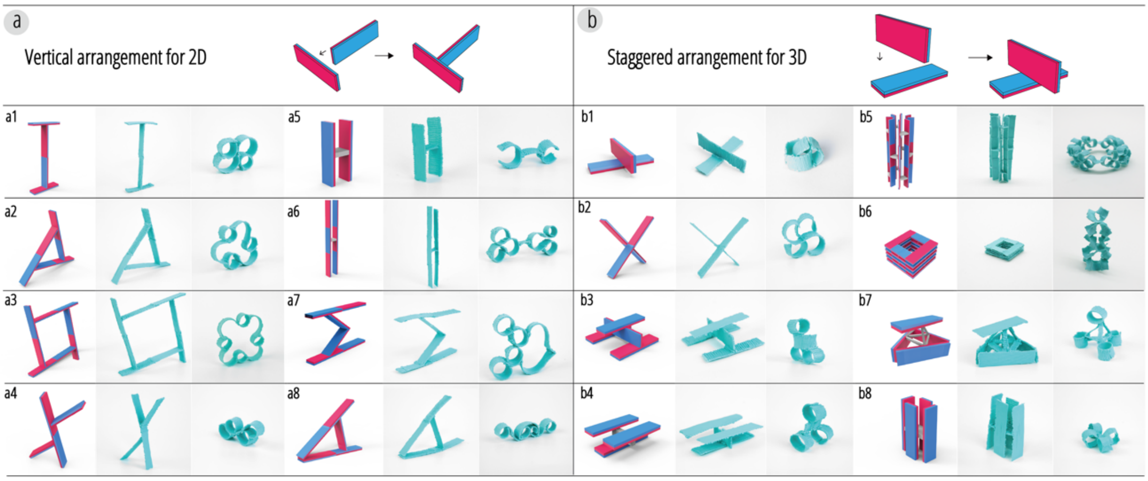

Figure 12: The shape library of assembling strips.

5.3.4 Assembling Before Triggering for Complex Structures. The arrangement design of assembly can transfer simple flat strips into complex structure in 3D spaces (Figure 11), which can provide a fundamental way to create geometric aesthetics. We utilized the composite structure of the strips as shown in Figure 11a to produce a shape library by assembling flat strips, for example, vertical arrangement of the standing strips can achieve 2D patterns after transformation in single axis (Figure 12a); staggered arrangement of standing and lying strips can achieve complex 3D shapes (Figure 12b), i.e., stretching structure (Figure 12b5) or popup structure (Figure 12b6).

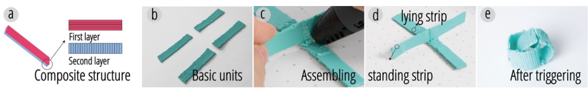

Figure 11: The basic unit for assembling.

5.3.5 Assembling While Triggering for Continuous Modification. Tinkering is a crafting method that allows users to make spontaneous modifications, which can speed up creative iteration. With 4Doodle, Users can continuously modify, iterate and gain inspiration from the assembling process and the item being made, such as the lampshade as shown in Figure 13 can be created by assembling while triggering multiple modules. Users can also assemble the 4D pieces with any handy pieces, for example, Figure 14 illustrate that the flower tree is assembled by a 3D printed trunk and morphable flowers by 4Doodle.

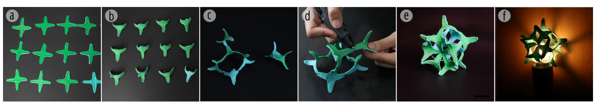

Figure 13: The lampshade was created using a technique of assembling while triggering.

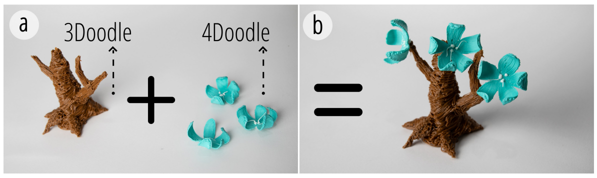

Figure 14: The flower tree was assembled by a 3D tree and 4D flowers.

6 MR SYSTEM TO ASSIST SKILL LEARNING

Our MR system combines the capabilities of computer-aided design and MR-guided crafting, implemented using Grasshopper (a visual programming language and environment that runs in Rhinoceros) and Fologram (a plug-in for Grasshopper and an app in iOS). The objective is to help users learn to perform hands-on printing independently and understand the relation between speed and deformation degree. The former contributes to data transfer and parametrical modelling, while the latter contributes to virtual presentation and interaction.

6.1 System Setup

To get started, the user needs to scan the QR code on a PC with the Fologram app installed on an iPad to connect the two devices. The user can then see the real world with the virtual cast interface and models via the iPad screen. In general, the user can create a final item within three steps:

- Step 1. The user chooses a basic model from our library and adjusts the parameters to achieve the expected result, shown on the screen.
- Step 2. The user may transform the chosen model into the desired form by array, mirror, rotation, etc.
- Step 3. The doodling path is displayed in real time virtually for the user, which helps the user doodle at an appropriate speed to achieve the desired deforming result.

6.2 User Interface

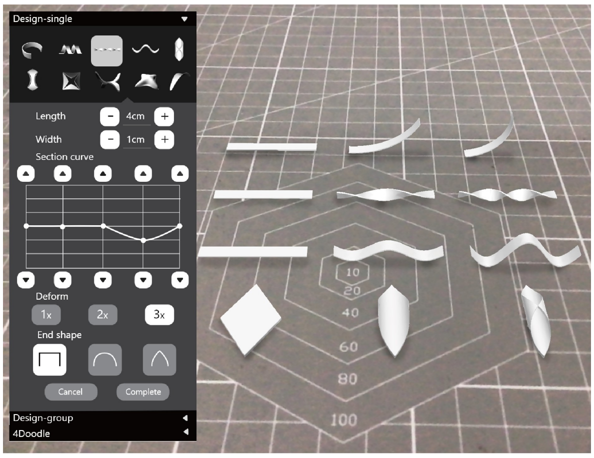

Figure 15: Users can start learning 4Doodle from a basic model selected from the design library, and the deformation can be visually simulated via MR.

6.2.1 Model Selection. Based on our primitive test, we integrated the structure library into the system. Users can choose any of these shapes as the basic model to learn and start designing. The original geometry of the selected model will appear in white for users to preview. Users can set individual parameters however they want (as per the tab below) to polish the geometry, e.g., the length and width of the surface, and the deformation that defines the bending angle. As Figure 15 shows, we display four models in our library, with the deformation increasing from left to right. We also provide a curve panel and end-shape selection for personalized boundary design, which enlarges the extension of our basic models. The previewing model will change according to the user's real-time taps, providing instant feedback.

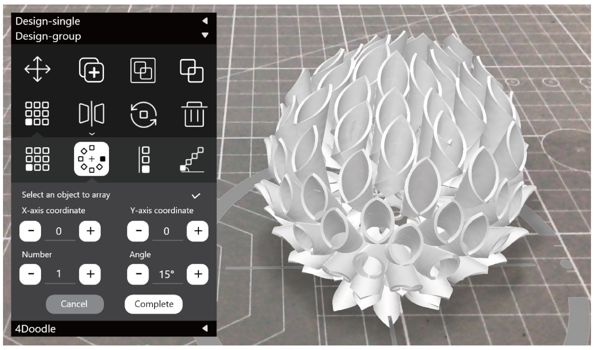

Figure 16: Users can design a complex structure using the quick design editor, and the expected result can be visually simulated via MR.

6.2.2 Simulation of Transformation. It is not always easy to imagine deformed objects during the design process, especially for complicated models like grouping ones. In this step, users can modify the basic transformation and directly preview the results, which may be hard to predict. We provide four types of arrays and four mirror choices with different mirror planes and directions. As for rotation, an initial rotating axis appears at the center of the geometry. Users can move the axis to a better position by tapping the buttons for a comfortable rotating result. After a series of transformations, users can see a final preview of the complete object. For example, Figure 16 presents a DIY lamp that is grouped by one of our unit models through polar array and rotation. This step can be skipped for novices and users who do not need transformation in their designs.

6.2.3 MR Guidance. As doodling directly determines the deformed result, it is essential to make this procedure controllable. Therefore, our system has precise path guidance. Based on the previous parametrical experiments in Section 5.1, the trajectory, layers and doodling speed in our system will automatically change depending on the model and deformation.

For each geometry, the trajectory is unique. To assist users directly, we cast the virtual trajectory into the real scene as an autoplay animation. As Figure 17b1 shows, the colored lines depict the printed part, while unprinted lines are in white. Gradient colors are used to simulate the moving effect and high transparency to make the path clear enough to follow. An intact layer will turn white after being doodled to avoid visual cluttering. Other essential variables include the layers and the speed, which are automatically set by our system. During doodling, users are allowed to pause or stop the guidance. Furthermore, they can repeat the animation an infinite number of times for learning and practice purposes.

In addition to trajectory guidance, our system also provides guidance for some expansive techniques as an optional module. Figure 17b3 shows the guidance for doodling on a mold. Users can choose a 3D mold and preview the trajectory animation. Green curves indicate a fast speed, while red indicates a slow speed. As for texture guidance, our system provides four kinds of textures as a reference (Figure 17b2). Users can click the "refresh" button for a new pattern as they desire. The system also provides some schematics to help users complete the post-process. As Figure 17b4 shows, the red zones and the white arrow indicate the connecting parts.

6.3 Computational Pipeline

6.3.1 Deformation Simulation. To geometrically represent the simulated deformed model, we first simplify each model on a planar surface. As each model deforms differently, various methods are applied in our system. Taking bending as an example, we assume that the curvature and surface length are constant, neglecting minor warping and shrinking. The resulting geometry can be represented computationally by calculating the effective radius using user-defined bending angle and length.

6.3.2 Data Interpolation. To integrate relatively precise speed guidance, we used a semi-logarithm regression to interpolate data collected through parametrical experiments (Figure 5). Based on the regressed function, we utilized a time trigger in the Grasshopper to move the yellow sphere along the path for a calculated distance within a specific interval. In addition to the trajectory and doodling

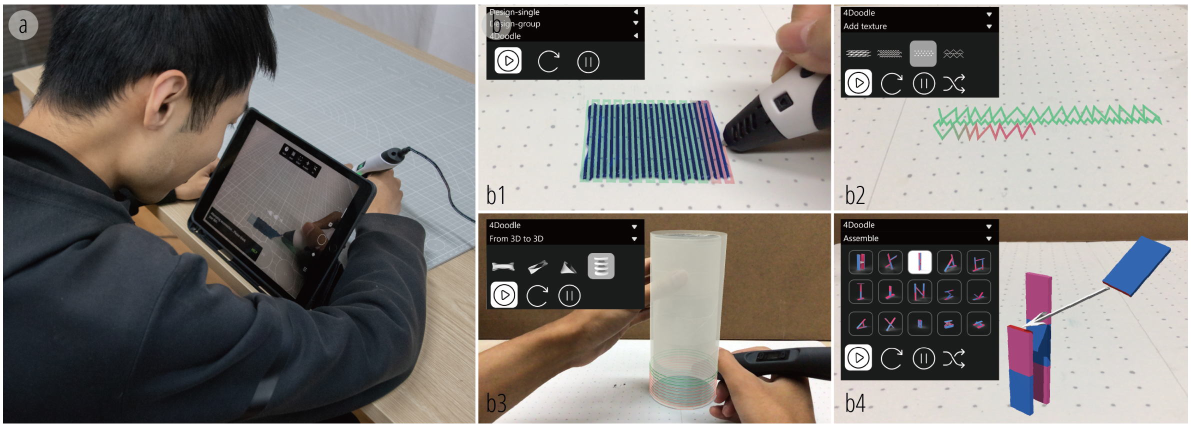

Figure 17: (a) Usage scenario with the craft-aided tool; (b) the interfaces for MR guidance while doodling.

Figure 18: Colorful animal finger covers using self-bending and self-spinning structures.

speed, our experiment showed that another key parameter is the layers. As layers influence the result to a certain extent (which is always a small integer), we only set two options for two layers and four layers, rather than interpolation, for simple calculations.

6.3.3 Trajectory Generation. As with the deformation procedure, each model possesses a unique trajectory. As the surface boundary varies, we divide each boundary into multiple segments with the same length. The corresponding dividing points are then linked according to the trajectory. For lines parallel to the x or y axis, points on the opposite boundaries are linked. In other circumstances, points on the neighboring boundaries may be linked. Finally, we need to link all the single lines end to end to get the complete trajectory.

7 DESIGN SPACES OF 4DOODLE

To better demonstrate the creative spaces of the 4Doodle method, we provide a series of cases for different contexts.

7.1 Enriching Handicrafts with Customized Structures

4Doodle provides makers and artists with a fast, accessible method to customize 3D structures on demand. Users can customize the color of the artifacts instantly by taking advantage of the 3D pen, which can quickly change printing filaments. To better demonstrate the customization of shapes and colors, we created a set of colorful animal finger covers by self-spinning a long strip into a spring to fit different fingers, and self-bending parts of the animal to make it more vivid (Figure 18), which took a total of 56 minutes. The windmill example (Figure 19) is created using seven pieces with a self-twisting structure. Utilizing a central rotating array and the connection with a fixed rod, the windmill can rotate. Figure 20 shows several practical products which adopt self-bending structures to meet personalized demand, such as phone holders, plant holders, key rings and hooks.

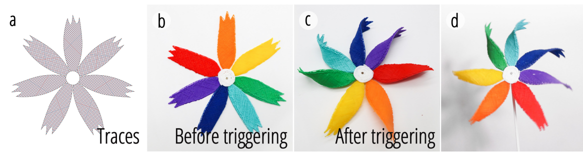

Figure 19: Windmill created by seven self-twisting blades.

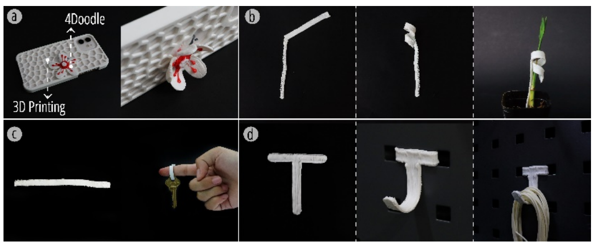

Figure 20: Practical products using self-bending structures.

7.2 Expanding Handicrafts with Various Combinations

Leveraging the stickiness properties of thermoplastic materials when melted and printed, users can quickly assemble and disassemble multiple modules and add decorations with a 3D printing pen. Figure 21 shows a 4D ikebana, which is the art of flower arrangement. Utilizing the reversible technique of 4Doodle, we 3D

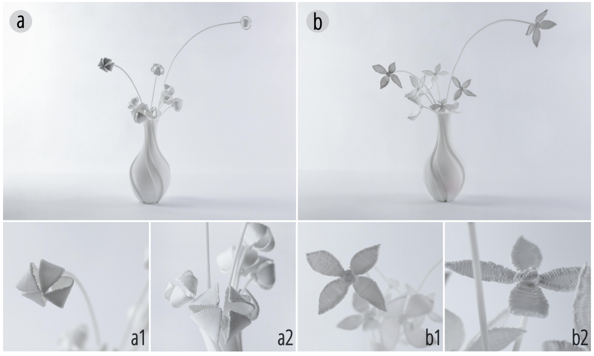

Figure 21: The flowers can be bloomed under heat triggering, using a reverse transformation from (a) curved to (b) flattened petals.

doodled petals on a curved surface separately and then assembled four petals into one bud, which took around 65 minutes for all seven buds. When triggering the buds using a heat gun, they can be unfurled as if blooming, one by one.

In another case, we provide a reusable module design, as Figure 22 shows. The module piece is flat-doodled into a 9 x 9 cm square shape which can transform into a cannoli shape. Users can assemble and disassemble these modules for open creation, such as a lampshade, a plate for fruit or a tree with lights on.

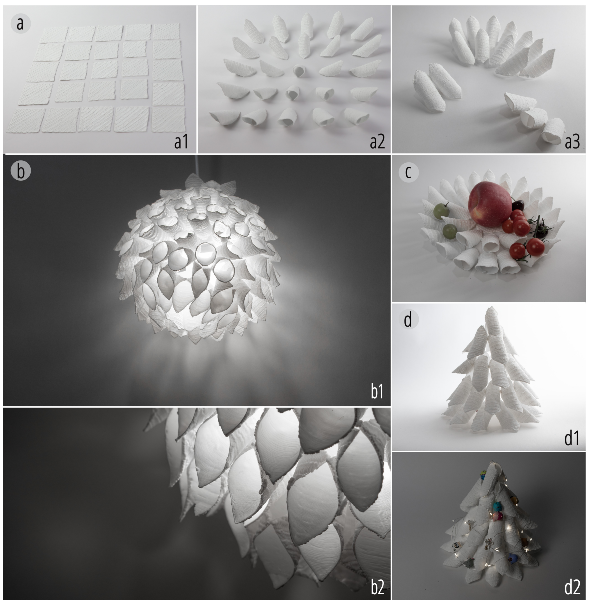

Figure 22: (a) The module pieces can be reused and transferred from (b) a lampshade to (c) a plate for fruit or (d) a tree with lights on.

Furthermore, users can add decorations to expand the visual and tactile sense of artifacts. For example, we demonstrate a series of shells with different textures to enhance the haptic feeling (Figure 23).

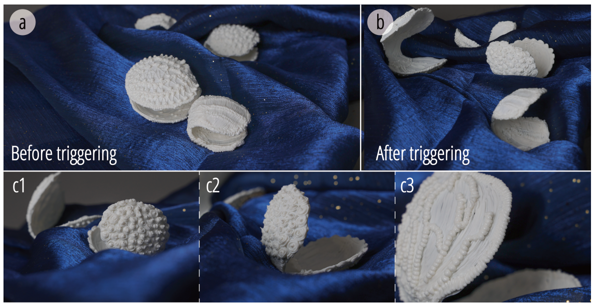

Figure 23: The series of shells with different textures can enhance the visual and haptic feeling.

7.3 Creating Handicrafts with Temporal Aesthetics

In addition to the customizability of the appearance and structure of artifacts, 4Doodle also provides a way to enhance temporal aesthetics while promoting shape-changing interaction. To better demonstrate this abstract concept, we provide three examples of deformation interaction. As Figure 24 shows, a morphable cartoon book realizes the plot of the story, through tangible transformation: "The baby elephant picks a flower for the giraffe, but the giraffe is too tall to reach it", so the illustrator guides children to trigger the morphable nose of the elephant to achieve the flower-picking goal. The tangible transformation can enhance the interactivity with children beyond visual images during storytelling.

Figure 24: Interactive storytelling with a morphable cartoon book.

In the art creation area, 4Doodle can provide new interactive dimensions of "time" and "deformation". As Figure 25 shows, an attractive art installation was created, containing a bunch of flowers around a light bulb, which got warmer over time, triggering the bloom in the first stage. As the temperature exceeded the melting threshold, the flower stem became soft and drooped, symbolizing the end of life. This transformation constitutes a tangible medium for the temporal aesthetic of philosophy.

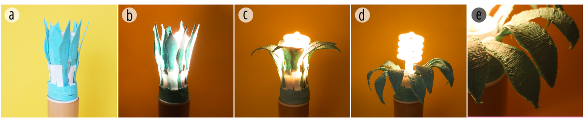

Figure 25: The flower fading over time is triggered by the increasingly hot bulb.

4Doodle can also serve as a new way to display the traditional art of painting, e.g., a 4D representation of Van Gogh's "Sunflowers", as Figure 26 shows. The petals of the sunflower are made of a self-bending structure, which can be triggered into a 3D shape by a heat gun. The heating process is also a creative process that can be freely controlled by creators.

Figure 26: 4D doodling of Van Gogh's "Sunflowers".

8 USER STUDY

To validate the skill-learning efficiency and usability of our MR system and investigate opportunities and limitations of the 4Doodle approach for creation, we recruited participants to learn and practice 4Doodle skills and produce a freestyle creation during a two-day workshop. In the next section, we present and analyze their reactions and feedbacks in terms of (a) how the MR system worked in the craft-learning process and (b) how the 4Doodle techniques affected the creativity of the 11 participants.

8.1 Methodology and Procedure

8.1.1 Participants. Eleven undergraduate/graduate students were recruited from the university (nine females and two males, mean age: 25.36 ± 3.26 years). All of the participants were randomly recruited regardless of their prior knowledge and experience of 3D/4D printing. All participants signed informed consent and received remuneration.

8.1.2 Apparatus. The main session of the user study was set up in a laboratory at the university. Identical materials and 3D pens as in the experiment above were prepared for all users. The participants were not restricted in terms of choosing the objects and materials to complete their designs, and they could use their own items or designs with the provided crafting tools and materials (such as tweezers, paper, rulers and clippers).

8.1.3 Procedure. The two-day workshop included questionnaire tests (Steps 1, 5 and 6), two skill-learning processes (Steps 2 and 3) and a freestyle creation process (Step 4). The detailed setting of the procedure was as follows:

Step 1: 20 minutes of pre-questionnaire tests (mental rotation and Cognitive Processes Associated with Creativity (CPAC) assessments).

Step 2: 40 minutes of skill learning and a practice session for 3D printing using 3D pens: the participants were taught how to use a 3D pen, including changing the speed and materials for different colors.

Step 3: The participants were given unlimited time to learn the requisite skills and practice 4Doodling: participants used the MR system to learn 4Doodle, especially the relation between speed and degree of deformation. Although learning time was not limited during this stage, we recorded the time it took participants to meet the measurement criteria listed in Section 8.1.4. If participants made rapid progress or found the device challenging, we taught them the five expansive 4Doodle techniques. Finally, participants freely used other functions of the MR system.

Step 4: This involved a one-day freestyle creation task: we presented participants with some design cases as examples and for inspiration and explained the design task entailing freestyle creation of artifacts, allowing them to plan a design idea in advance. During the one-day experiment, participants worked on their designs using 4Doodle in the lab. During this section, we mainly investigated users' creativity and the quality of their output.

Step 5: This involved a 20-minute post-questionnaire test (mental rotation and CPAC assessments).

Step 6: In this step, participants spent between 8 and 18 minutes completing a self-report questionnaire and interview. The self-report questionnaire used a seven-point Likert-type scale [38], and participants were asked to self-evaluate their experience with freestyle creation (Step 4).

8.1.4 Assessment. To assess the skill-learning efficiency and usability of 4Doodle, we set up a learning session without a time limit (Step 3) and recorded the exact time taken and process through which participants successfully mastered use of the MR system and 4Doodle techniques. Two measurement criteria were used to rate the learning time: 1) participants successfully understanding the mechanism for creating composite structures, controlling printing direction and printing speed; 2) participants successfully making a deformable sheet. A self-report questionnaire (Appendix A.1) was used to assess the usability (Step 6).

For the human intervention side, a previous study [55] has explored the importance of HCI system on human cognition. For instance, Buehler et al. found that human cognition can be effectively affected by 3D printing technology in educational setting [56]. Based on the above approaches, we aimed to test how 4Doodle can influence people's cognitive abilities (i.e., creativity and spatial ability) and also sought to explore its possible implications in maker space. We set up a freestyle creation task (Step 4) using the mental rotation test[1] to evaluate spatial ability (Steps 1 and 5), and the

[1]The mental rotation test was used to measure spatial ability [57], in which participants were allowed to identify the correct matching shapes for objects oriented at different angles. The test consisted of 12 questions and two correct answers for each question. The total mark was 24 if the participants answered all questions correctly. The questions for the pre-test and post-test were entirely different to prevent respondents from answering these questions according to memory.

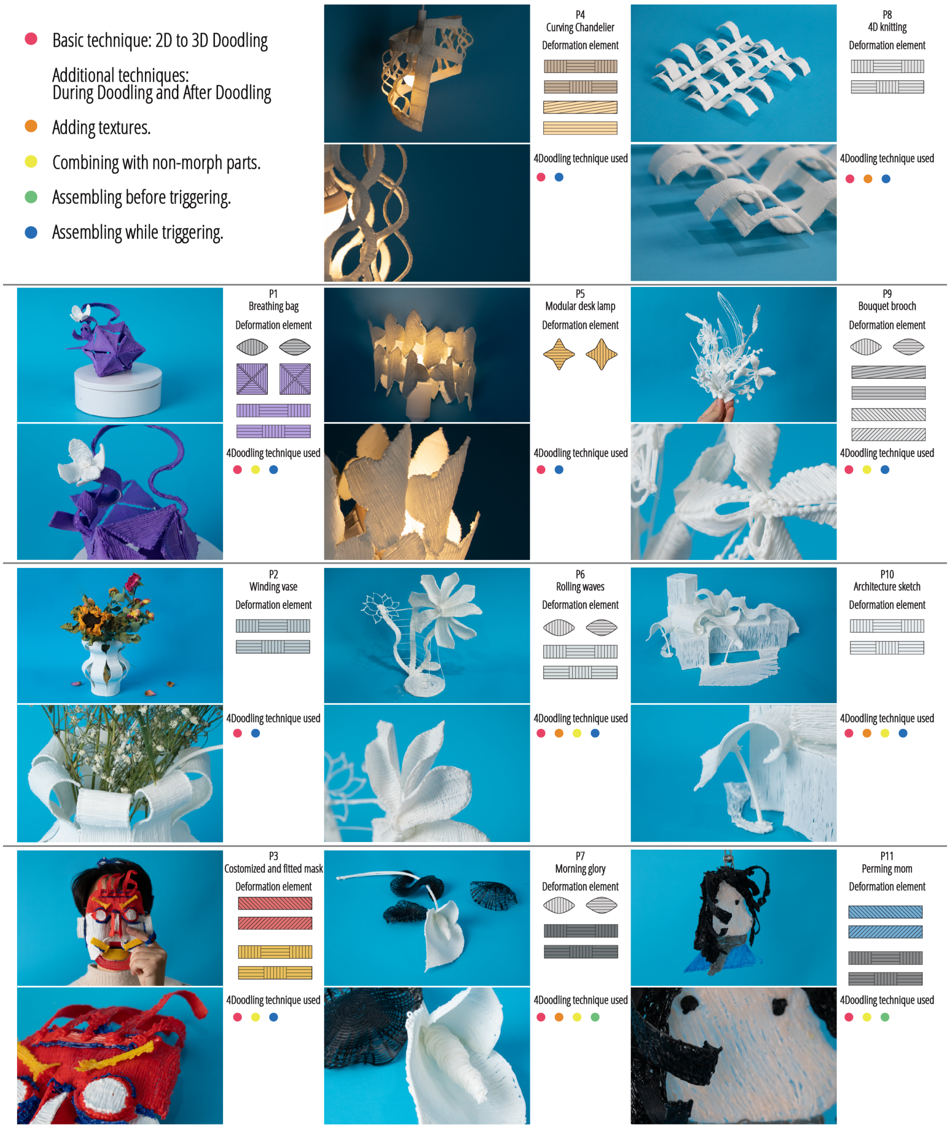

Figure 27: Outcomes of the 4Doodle workshop (artifacts made by the 11 participants).

Cognitive Processes Associated with Creativity (CPAC) test[2] to evaluate creativity (Steps 1, 5, and 6).

8.2 Outcomes, Results and Reflections

Overall, most participants were positive about the MR tool and the 4Doodle techniques. They were able to grasp the skill of hands-on 4D printing and finally create morphable artifacts, as presented in Figure 27. From these outcomes, we found that participants utilized more form and function in their free exploration than the techniques and reference cases provided. For example, some participants explored the method for assembly of modules, according to their design goals: P8 used the interspersed layout of the wave modules in space to create a knitted effect, which is difficult to achieve in 3D printing; P2 placed the wave modules that are usually horizontal in a vertical position and then made a vase through the center-rotating assembly method; P5 utilized the different four-leaf clover shapes in the morphed module to design a lampshade assembly, *"realizing a casual and natural aesthetic feeling under the*

[2]The CPAC test [58] uses a five-point Likert-type scale to measure human creativity. It was scored based on five dimensions: incubation, brainstorming, perspective taking, imagery and flow. The score for each dimension was summed for some unique questions, and a higher score represented a higher degree of creativity.

light". Some participants adopted a combination of techniques to join 4D parts to non-morph parts using technique number 5, such as a bag with a wavy handle (P1), a lampshade with a curved frame (P4) and a desktop windmill (P6). Some participants tried to express their artistic ideas through a dramatic curved 4D appearance, e.g., a colorful mask (P3), a flower (P7), a brooch (P9) and perming mom with curly hair (P11). Another participant (P10) utilized 4Doodle to prototype a form of architecture from his major experience.

8.2.1 Learning Efficiency of MR Tool. In the guided exercise for MR tools, participants could master the relation between speed and bending in a short period of time and successfully doodle flat sheets that could be morphed. The average skill-acquisition time was about 8 minutes, and the fastest was only 4 minutes. Compared with learning 3D doodling without software tools (Step 2), three participants commented that the efficiency of learning improved dramatically because the tool provided visual information about speed and trajectory: *"At first, my hand was chasing the guidelines, and after about 10 lines I felt like I was getting used to that speed."* (P2)

In the feedback on software usage, participants also made some suggestions for improvement. P10 suggested showing an overview video at the beginning of the guidance "*to take control of the overall process and take some of the anxiety away"*. P3 suggested inclusion of feedback on errors or on correct use: *"I want to know exactly if I drew it right or wrong."*

8.2.2 Human Intervention with 4Doodle. The 11 participants completed the pre- and post-cognitive ability questionnaires. The data from three participants were eliminated because they reported that they did not thoroughly complete the measurements because of fatigue effects. Independent sample t-tests were used for pre-and post-assessment comparison. As shown in Figure 28 (Appendix A.2), testing for mental rotation ability demonstrated a significant difference ($p = 0.04$), and participants performed better in the post-test (mean ± SD: 11.19 ± 0.84) than in the pre-test (9.75 ± 1.58). A significant difference was also found in the incubation dimension in the CPAC test ($p = 0.046$), and it showed a significant improvement in the post-test (22.63 ± 2.56), compared with the pre-test (19.00 ± 3.93). The results validate that human cognitive ability improved significantly after using 4Doodle, including spatial ability and incubation creativity.

8.2.3 Hybrid Engagement of 4Doodle. To better assess the overall usability of 4Doodle in the hybrid engagement experience, we further analyzed the participants' self-reports. The average scores were high in many dimensions, including flow, engagement, satisfaction and collaboration (see Appendix A.1 for the full self-report results).

For the flow dimension (6.50 ± 0.75), even though the duration of the free style creation session was very long, participants reported that they thought the time went by quickly when designing their work, with one participant saying, *"Before I knew it, two hours had passed."* (P10)

A high score in the engagement dimension (6.63 ± 0.74) indicated that the participants were able to engage in the creation activity, with one participant saying, *"The craft method was handy, and I would like to use it for future design."* (P1)

Users scored highly in the satisfaction dimension (6.38 ± 0.92) and demonstrated that they liked 4Doodle, even though there was no comparable level in the ownership dimension (5.13 ± 1.25). Two participants addressed the scoring and gave similar answers: *"I think it is easy for designing my work using 4Doodle because the deformation library provides basic components, and I also could conduct the creation as freely as possible."* (P7)

The results also showed a good effect for collaboration between users and our software system. Participants indicated that the efficiency of the creation process was improved with the support of the software (6.50 ± 0.53), and they became more confident when using this system (6.00 ± 0.76). During the creation session, three participants reported that they revisited the library to preview the deformation simulation and were inspired by the elements in the library: *"The deformation library and case saved a lot of time, and I chose the four-leaf clover as my design element."* (P5); *"During my freestyle creation, I became interested in deformed spatial structure design through the simulation preview in the software."* (P8)

9 DISCUSSION, LIMITATIONS AND FUTURE WORK

9.1 Accuracy Limitation and Considerations

Although our MR system helped to improve the success rate and precision of the deformation, 4Doodle has limited accuracy compared to machine printing because of the uncertainty associated with human performance. Furthermore, the guiding parameters were obtained through the fitting function of the data from our manual experiments, and they have a relatively large error range. The environmental conditions, with a degree of indoor humidity, might also be an influencing factor.

9.2 Cognitive Load of MR Software and Improvements

Although our MR system casts the virtual scenes into reality, a certain cognitive load may occur when users doodle while staring at the screen. As the participants expressed, it took several attempts to adapt the way they doodled. To provide a better experience, we believe more functions need to be included; for example, deforming is a key process to intuitively understand 4D printing, and optimized simulated animation of deforming is a promising direction for future work. Furthermore, we intend to introduce more doodling techniques and design spaces while supplying continuous representation in the MR system through updating the device.

10 CONCLUSION

In this paper, we have presented 4Doodle, a 4D printing method with a 3D pen that allows users to doodle self-morphing handicrafts. To provide technical standards and guidance for using 4Doodle, we investigated potential influencing factors in deformation and summarized five 4Doodling techniques through extensive experiments. We developed a crafting tool embedded in an MR system to enable novice users to learn the requisite skills and preview their designs. Furthermore, we have demonstrated the creative possibilities by providing several 4Doodle design cases. Finally, a formal user study verified that our 4Doodle method can significantly lower the barrier to crafting learning and possesses a high degree of usability and effectiveness in terms of improving users' creativity and spatial ability.

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A APPENDICES

A.1 The Self-Report Questionnaire and Results

Table 1: The statements of the self-report questionnaire were scored by users using a seven-point Likert-type scale.

Self-Report Questionnaire	Score Mean ± SD
1. I like the work that I created. (Achievement)	5.73 ± 0.65
2. I was able to create what I expected. (Expressive)	5.27 ± 1.10
3. I think the working time was long. (Flow)	6.18 ± 1.25
4. I think that it would be hard for others to replicate my work. (Ownership)	4.73 ± 1.35
5. The system allows me to produce my idea quickly. (Exploration)	5.36 ± 1.36
6. When planning, I was able to imagine how I would use the system. (Expectation)	5.55 ± 0.82
7. I was very engaged in the activity. (Engagement)	6.55 ± 0.69
8. I like the printing system.	6.27 ± 0.90
9.The printing system improved the efficiency of the activity. (Collaboration)	6.18 ± 0.75
10. I was more creative and successful when I used the system. (Collaboration)	5.91 ± 0.70

A.2 Performance Results in the Human Intervention Test

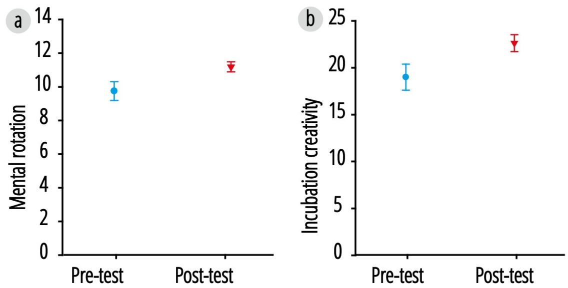

Figure 28: Performance results for the cognitive ability test.