A COMPARATIVE EVALUATION OF AUGMENTED REALITY LEARNING TECHNIQUES AND TRADITIONAL LEARNING MATERIALS FOR BEAD WEAVING

by

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Abstract

The most common learning materials for handcraft today are videos and figures, which are limited in their ability to express embodied knowledge as an in-person tutor could. I developed EmbodiAR, an application for headworn augmented reality (AR) displays designed to teach beginner bead weaving patterns using virtual 3D hands that show weaving sequences recorded from an experienced bead weaver and a dynamic 3D bead model showing how the work progresses. Using a mixed within/between-subjects user study (n=30), I compared the learning materials (AR to videos and figures) and learning material placement (area of work or to the side). Quantitative and qualitative data analysis shows that the AR learning materials had comparable effectiveness to video and figures. Hand visualizations were found to lack crucial context, however, making them less useful than the 3D bead model. Extra measures to prevent obstruction are required when placing learning materials at the area of work.

Acknowledgements

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Chapter 1

Introduction

Learning materials for handcraft (bead weaving in particular) is primarily dominated by figures, videos, and blog posts [62, 71, 77]. Craft knowledge is built from examples of experience where learners develop an “efficiency and rhythm” [80] in their work which is then internalized as embodied knowledge. However, these traditional 2D learning materials are limited in their expression of embodied knowledge. Figures cannot fully illustrate the movements required to do the activity, and require the observer to infer the movements required. Videos can illustrate the movements of the hands, but are often limited to a fixed perspective where the observer needs to orient themselves to the perspective of the video. This begs the questions if learning materials targeted towards conveying the embodied knowledge of an experienced craftsperson would be more appropriate for learning handcraft.

Headworn augmented reality (AR) allows for virtual content to be overlaid onto the real world, while keeping the user’s hands free. State-of-the-art AR devices such as Microsoft’s HoloLens 2 [55] can provide a high quality experience which has not been readily available in the past. Modalities such as hand tracking allows for understanding of the hand’s placements and movements. This opens up the possibilities of recording and visualizing the hand movements of an experienced craftsperson and relaying it to a learning novice. In addition, modalities such as voice commands and eye tracking allow users to interact with systems without using their hands. This allows a craftsperson who’s hands would be occupied with the tools and materials to interact with the system. Lastly, the spatial properties of the holograms provide an opportunity to explore the placement technique of learning materials. As videos and figures are usually either displayed through a computer monitor or on paper, the dynamic placement of having the learning material at the area of work could make it easier to compare the virtual and physical materials.

Prior research explores the capturing embodied knowledge in the context of handcraft utilizing hand tracking technologies. Furthermore, existing work covers integrating AR with handcraft and learning hand-based tasks in AR. However, there is a gap in the research surrounding the evaluation of teaching bead weaving and handcraft skills within AR. Prior work has explored other mediums for conveying handcraft such as virtual reality (VR) which offers a rich immersive experience. However, VR's immersion is not suitable when the learner is utilizing their own tools in the real world, as they would not have the visual context of their work.

As handcraft features a wide assortment of disciplines, domains, and tasks, I focus on bead weaving for the purpose of this research. This is due to the reliance on video and figures and the constrained nature of bead weaving tasks for beginner stitches.

This research is part of an interdisciplinary project called Gesture and Form. I developed a headworn AR application called *EmbodiAR*, which is designed to use new learning materials designed to convey embodied knowledge for learning handcraft using three different approaches. For my research, the scope of the application is currently limited to bead weaving stitches.

I use EmbodiAR as a tool in a mixed within/between-subjects user study to answer two research questions. The first investigates how the new AR-based learning material (dynamic 3D bead model and 3D virtual hands) compares to the traditional learning materials of videos and figures. And second, investigates how the placement of the AR-based learning materials at the area of work compare to a more traditional side-by-side placement.

I found the new AR learning materials compared similarly to the combination of videos and figures. However, there was a larger difference in the helpfulness within the new AR learning materials in comparison to the difference within videos and figures. The dynamic 3D bead model was noted to be much more helpful than the 3D virtual hands due to a lack of context of the work with the hands. This shows a greater reliance on the form of the work that is being achieved rather than the gestures required to complete the work. Additionally, this questions the utility of hand-based recordings of a craftsperson alone to convey embodied knowledge as it is not helpful as a learning material without additional context. I also found there were no significant differences between the learning materials being placed at the area of work or on the side. However, there were instances where the 3D virtual hands at the area of work was disruptive. Extra measures to prevent obstruction are required when placing learning materials by the area of work. I found participants interacted with the AR learning materials similarly across conditions, and that voice commands were the preferred interaction technique as they could focus on the work with their eyes and not have to interrupt the task at hand.

The thesis is structured as follows. First, I present my literature review to establish the current bead weaving and craft practice alongside similar systems and techniques. Then I present my preliminary work which details my involvement with Gesture and Form and the prototypes I have created. Then I detail EmbodiAR, justifying the design choices for the learning materials and detailing the system architecture. Then I present the evaluation component, which includes the design of my user study and data analysis structure. Following are the results from the user study I conducted. Then I provide a discussion regarding the implication of the results alongside current and future work. Finally, I conclude with my final contributions.

Chapter 2

Literature Review

2.1 Introduction

I followed a two-phase literature view search process. I introduce the background of bead weaving and then cover current learning practices. As the knowledge from bead weaving is based on hand movements, I introduce the concept of embodied knowledge. Furthermore, I cover research on the traditional learning materials (videos and figures) and how the embodied knowledge within the hands is captured.

I introduce AR and elaborate on state-of-the-art AR features and how they are incorporated within my research. I cover how AR systems are developed alongside guidelines which informed the design and development of my work.

Once both bead weaving and AR are covered, I introduce learning applications for AR systems, first for craft specifically and then with hand-based tasks as it relates to bead weaving.

As VR is a similar medium to AR, I explore handcraft applications within VR and other non-AR mediums such as tangible computing.

2.2 Literature Review Search Process

I reviewed the literature in a phased approach. For the first phase, I did a wide breadth search for any relevant literature in the past three years. For the second phase, I followed a snowballing approach. Throughout the Gesture and Form project we discussed weekly readings on the intersection of our interdisciplinary project (e.g., architecture and craft within AR, bead weaving, and implications of cultural heritage), which diversified my literature review. In addition, I explored and saved references as needed to round out the background.

2.2.1 Phase One: Broad Literature Review Process

For the first phase, I conducted a wide breadth search across multiple conferences of interest for relevant research articles.

This process involved scanning all title of papers in the last three years searching for only research articles. If the paper title indicated any potential relevance, I then reviewed its abstract. If the abstract confirmed its relevance, the reference was saved with a note of why I thought it was relevant. All papers who did not confirm relevancy were skipped. Following the scanning, the papers which had potential relevancy were skimmed to confirm its relevance.

My focus during this phase of the literature review were on the following conferences:

1. The ACM Symposium on User Interface Software and Technology (UIST),
2. IEEE International Symposium on Mixed and Augmented Reality (ISMAR),
3. The ACM International Conference on Tangible, Embedded and Embodied Interaction (TEI),
4. The ACM International Joint Conference on Pervasive and Ubiquitous Computing (UBICOMP),
5. The IEEE Conference on Virtual Reality and 3D User Interfaces (IEEEVR)
6. The ACM Symposium on Virtual Reality Software and Technology (VRST),
7. The IEEE Visualization Conference (VIS),
8. The ACM Conference on Human Factors in Computing Systems (CHI).

The literature review took one month in duration from May 3, 2021 to June 3, 2021. The quantitative results from this literature review process can seen in Table 2.1.

Table 2.1: Phase one literature review quantitative results

Conference	**Search Key**	**Number of Results**	**Number of Potentially Relevant Research Articles**
UIST	Given date range (01/05/2018 TO 31/05/2021)	278	23
ISMAR	ISMAR 2020 ISMAR 2019 ISMAR 2018	70 36 18 (Subtotal: 124)	9 3 2 (Subtotal: 14)
TEI	Given date range (01/05/2018 TO 31/05/2021)	157	14
UBICOMP	Given date range (01/05/2018 TO 31/05/2021)	439	8
IEEEVR	IEEEVR 2021 IEEEVR 2020 IEEEVR 2019 IEEEVR 2018	92 104 473 250 (Subtotal: 919)	4 2 15 3 (Subtotal: 24)
VRST	Given date range (01/05/2018 TO 31/05/2021)	93	5
VIS	VIS 2020 VIS 2019 VIS 2018	59 59 (N/A) (Subtotal: 118)	0 0 (N/A) (Subtotal: 0)
CHI	Given date range (01/05/2018 TO 31/05/2021)	2512	45
TOTAL		**4640**	**133**

2.2.2 Phase Two: Snowball Literature Review

The next step was to identify more articles using the snowballing procedure defined by Wohlin [84] which is visualized in Figure 2.1. I identified a list of 29 articles of interest from phase one by evaluating the relevancy of this research. I then looked forward and backward through the citations until no new papers were found.

This literature aided in verifying this is a new contribution and has not been done recently with current state-of-the-art AR technology and bead weaving information.

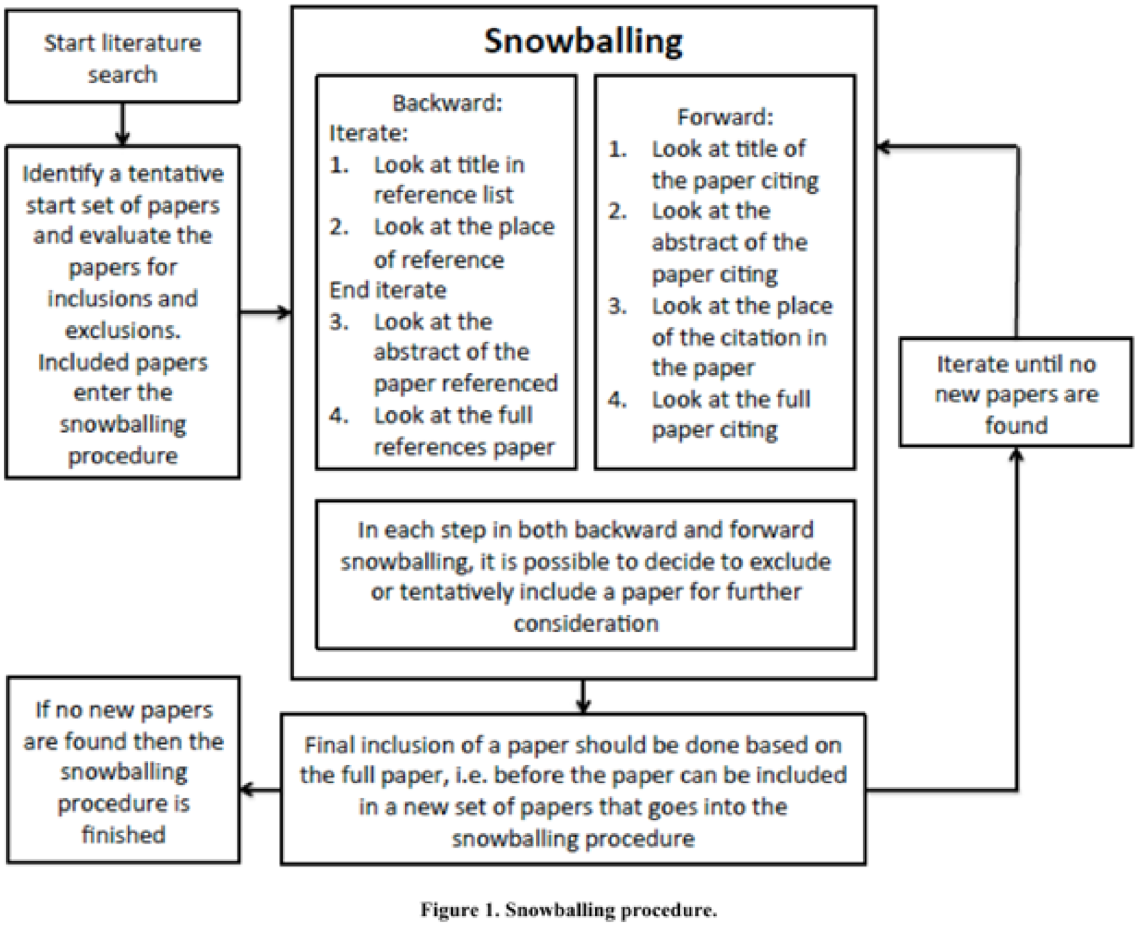

Figure 1. Snowballing procedure.

Figure 2.1: Snowballing procedure [84] used in phase two of literature review

2.3 Bead Weaving and Craft Practice

2.3.1 Bead Weaving and its Implications in HCI

For my research, bead weaving is a fundamental area of focus. *Bead weaving* is defined as a beadwork technique where seed beads are woven together using a thread to create a resulting beadwork [4]. Bead weaving has a rich history rooted in cultural heritage and the earliest beads date back to 108,000 B.C. [19]. Bead weaving can be done by hand or mechanically with a loom. While there exists research for improving automation of craft [39, 33], Deshpande et al. [16] note how these machines "bypass the learning experiences". For my research I focus on bead weaving done by hand.

When bead weaving by hand, there is the tapestry needle, thread, and beads. As illustrated in Figure 2.2, the needle and thread are attached on one end, and a bead is attached on the other end (known as a *stopper bead*), which keeps the new beads from falling off the thread. I focus on two primary actions learned in bead weaving: *string* a bead (i.e., add a bead onto a needle) and *thread* a bead (i.e., push the needle through a bead in the beadwork to create a stitch).

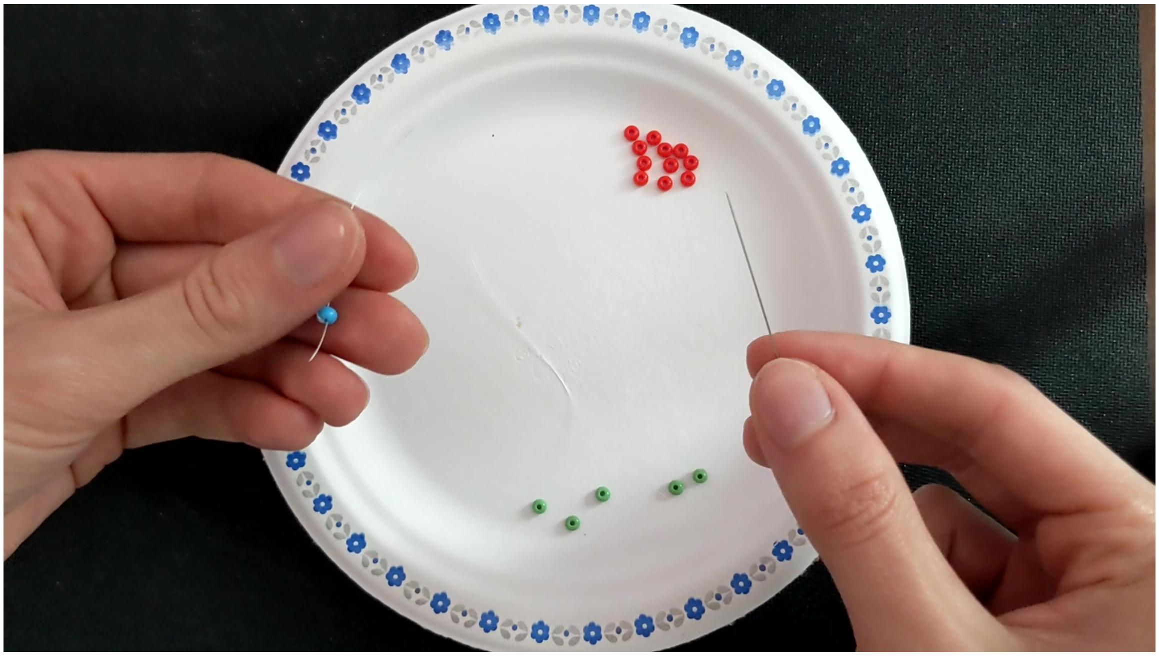

Figure 2.2: Bead weaving materials

New research within Human Computer Interaction (HCI) has considered using technology to preserve and spread Intangible Cultural Heritage (ICH) such as archiving the bead weaving craft process. However, there is tension between using new technologies and respecting the knowledge from cultural communities. Kotut et al. [42] define a scale known as the *Respectful Technology Space* for Indigenous Knowledge (IK), which illustrates what categories can respectfully be used for preservation and dissemination of IK. The scale uses two variables: the *location* and the *content*. IK can either be bound or unbound to a specific location, and the content can either be reserved or unreserved. Craftsmanship falls under the category of *sacrosanct* which refers to the space of which content is reserved and location is bound, and most importantly that technology should not be used at all within cultural communities. They imply that sacrosanct knowledge should only be passed directly and not recorded where unauthorized people could potentially see it. Such that the responsibility for transferring craft knowledge is through knowledge holders within the community via word of mouth. Thus, learning technologies for craftsmanship are not appropriate in these cultural communities. This classification provided by Kotut et al. [42] is derived by interviewing 11 participants comprising of museum docents and community members including cultural experts in the North-Right region of Kenya. They explored how the museum represented the community's culture and probed the role of technology. Then, they performed a thematic analysis on the interview transcripts.

The importance of safeguarding craftsmanship is also reinforced by Lu et al. [49], who explore live streaming ICH activities, primarily based in craft in the cultural context of China. They conducted semi-structured interviews with ten streamers and eight viewers to understand their practices. Using an open coding method on the transcripts, they found "ICH streamers were less motivated by financial benefits but were motivated by self-perceived responsibilities to safeguard the cultural practices of their expertise" [49]. They encourage community participation to assist in safeguarding ICH. The knowledge holders within this focus use technology (i.e., video streaming) to preserve and share the craft knowledge from their culture, which contrasts the above where technology should not be used.

Thus, it is important to consider how bead weaving as a form of craftsmanship is approached today. Just as it is an important role to safeguard craftsmanship, it is also important to respect cultural heritage. As seen above, there is a clash between technology being inappropriate for preserving craftsmanship while others utilize technology to safeguard their culture's craft knowledge. For my research I explore the preservation and dissemination of novice bead weaving techniques, however, I focus on contemporary beadwork to respect the cultural origins of the craft. If this research were used within a specific cultural group, potential issues such as unauthorized access to the knowledge could occur. The effect of that could directly negatively impact that culture as the generated artifacts could be learned to be mass produced and reduce the sacredness of the artifact.

In another vein, Devendorf et al. [18] argue how HCI needs to collaborate with craftspeople during early stages and not after the technology is developed. By collaborating with a craftsperson through an experimental weaving residency, their contribution focuses on broadening awareness of HCI practices of integrating craftspeople. Throughout my research, I followed this approach by being part of an interdisciplinary project following a user-centered design process and deriving insights from bead weaving/craft experienced collaborators.

2.3.2 Current State of Learning Bead Weaving and Craft Practices

To motivate the learning resources used in my evaluation, it is first important to know how people currently pursue craft knowledge.

Kross et al. [44] explore what and how people learn online using a national survey from 2260 US adults aged 18 and over in June-July 2019, who are balanced to match the demographics of the United States. With a 62.4% proportion of the respondents, the most popular subject learned online is do-it-yourself (DIY), which includes cooking, baking, and most importantly arts-and-crafts. They also report that for subjects like DIY, respondents learned more from informal resources over formal resources. Figure 2.3 illustrates how the respondents learned DIY: YouTube was used by 28.4%, how-to guides are used by 20.7%, then reading and asking questions on Q&A forums (25.4% and 20.3% respectively). Although cooking and baking are included in these statistics, it does help illustrate how those interested in crafts approach learning.

In Denmark and Norway craft practice today (2021) is learned in formal educational institutions, informal social learning mediums (arts and craft communities,

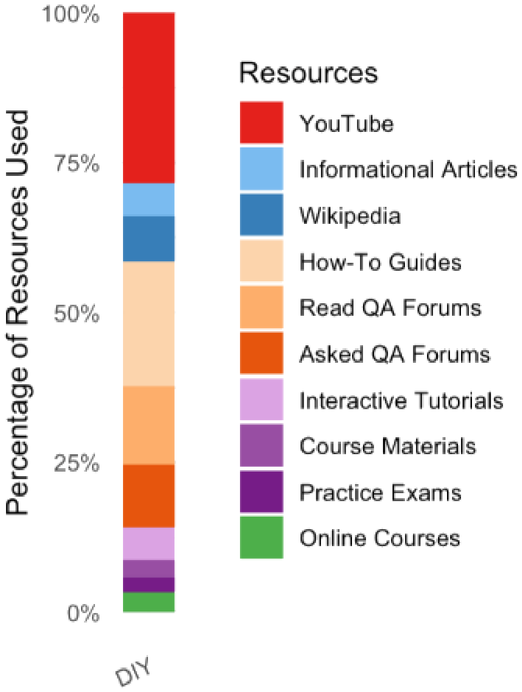

Figure 2.3: Proportion of resources learned for DIY subjects from survey collected in June-July 2019; augmented figure from Kross et al. [44]

classes, afternoon clubs, etc.), or informal individual learning mediums (online learning courses and materials such as video and blogs on the internet) [62]. This is based from Møller's and Riis' own practices which are deeply rooted in crafts with a focus on textile craft.

Online informal guides for novice bead weavers [71] suggest that learners watch online video tutorials, seek bead weaving classes (either in person at a craft store or online), or download bead weaving image patterns.

Similarly in 2009, Torrey et al. [77] explored how people find craft knowledge. Two methods they report involve being taught in person by an expert or utilizing forums to ask and answer questions based on their work. An aspect both of these learning mediums feature is communication with experienced craftspeople. Three other methods mentioned for independent learning include: how-to videos, blogs, bead patterns. These methods generally contain figures, videos, text, and audio.

It is important to consider how craft is learned in cases where users may not have equivalent abilities. Das et al. [15] focus on design and research for accessible crafting. They conducted “eight months of participant observation at a communal weaving studio for people with vision impairments” [15] and conducted contextual interviews with the weavers and instructors. They observed that instructors would place their hands over the novice weaver’s hands in early learning to help guide their hands as they describe the key steps in weaving. This utilizes the tactile sensation of the work and audio of instructions to aid in teaching the required movements. As the learners became more familiar with the weaving process, the instructors would move from embodied guidance to primarily verbal instructions. Thus, an avenue of learning is through hand movements based on the location of the user’s hands. While AR does not have the ability for physically guiding the user’s own hand movements, it can try to use augmented visual aids at the place of learning to guide the required hand movements for those who are not visually impaired.

These sources suggest that novice bead weavers and learners of other handcrafts have in the recent years tended towards resources such as video tutorials and pictorial figures for independent learning resources, particularly where expert craftspeople are not available. I will be referring to videos and figures as the traditional learning resources for bead weaving in current craft practice today. I use these traditional learning resources as a base of comparison for my research.

2.3.3 Embodied Knowledge

Embodied knowledge as described by Tanaka [75] is “a type of knowledge where the body knows how to act”. It is further described to a be a type of knowledge that is not “distinctly explicit, conscious, mentally representative, or articulated” [75]. Essentially, the body learns the implicit knowledge from doing the task. In the context of bead weaving, developing embodied knowledge is the goal when learning a new stitch. When a learner reaches proficiency at stringing and threading a stitch, the act to continue is effortless as the hands do the work without conscious effort from the bead weaver.

Westerlund [80] highlights the importance of hand knowledge in craft with a focus on plant propagation. They declare “craft knowledge is built from examples of experience, and when experiences from many people are gathered and compared, new knowledge is developed" [80]. Additionally, knowledge that is difficult to put into words may not be communicated between craftspeople due to the increased difficulty to describe. Westerlund answers the question on what theoretical perspectives and analytical tools support the development of methods for communication of craft knowledge via analysis of two different cases of communication in community practices: plant propagation and spruce hedging. They cover the practice of how craft knowledge is transferred. The findings show socialization between craftsmen is not always common and how skills in communication are required across all craft fields. In my research, I have provided a tool to document and visualize craft knowledge, which could be used to facilitate communication of skills by requiring less effort from craftspeople.

Baurley et al. [2] explored embodied knowledge in cooking and describe six categories of embodied knowledge which capture the desired dish. Similar categories could be used to describe the embodied knowledge in bead weaving.

1. *Material* to describe the context of the work. For bead weaving, I analyze the quality of the beadwork generated.

2. *Body* to use elements of the body to measure quantities. For bead weaving, this could be used to describe the tension within the thread of the beadwork, however this would be difficult to measure and not explored in this thesis.

3. *Technique* of using utensils. The utensils in the case of bead weaving would be the needle. This thesis explores the behavior of novice bead weavers and how they interact with the learning materials.

4. *Time* to measure quantity over a set duration. In my evaluation, I utilize a fixed duration and measure the quantity of work done for the generated beadwork.

5. *Memory*, a relative measure of adjustment from a previous experience. In my evaluation, novice bead weavers were given the option to redo the beadwork to try to avoid encountered issues. Additionally, as in my evaluation, I probe for strategies learned between different trials.

6. *Traces*, to visually communicate the path taken from a technique. I incorporate this into the AR learning materials to visualize the path taken from a needle

from an experienced bead weaver.

2.3.4 Traditional Learning Material

Videos and figures are traditional learning materials for learning crafts with bead weaving as focus. I will now cover existing work with these traditional learning materials.

Heinemann and Möller [32] study novice knitters and how they learn to knit by following instructions from a video tutorial. They motivate this self-directed learning option as they recognize experts are unable to always monitor the learner. They designed a natural experiment where nine participants watched a popular YouTube video on learning knitting, designed for novices with no prior experience. They investigate the participant's understanding based on their actions and reactions to reveal "what each of the novice knitters do and in particular how and where they do it in relation to the instructions given in the video tutorial" [32]. From their excerpts, participants position themselves seated directly in front of the laptop with their work in front of them, however no analysis on their positioning was provided. From the common approaches found, the first focuses on failing to recognize the first error. As the states in the video progress, the participants make an attempt at performing the step following the mistake. Only once they realize they can no longer follow the instruction and there is a visible difference with their work, did they recognize an error occurred. They argue novices are forced to explore by themselves and this is seen by novices iterating on their errors. Another notable behavior was that they used the video's controls to step through the video to points where the yarn was visible, essentially segmenting the tutorial into a collection of figures. They also found in order to navigate the video that the participant would have to repeatedly gather their work in one hand to free the other for interacting with the video. As knitting requires the use of both hands (holding the yarn and needle), they find the traditional video control affordances impractical. Knitting is comparable to bead weaving, a handcraft that uses a needle and a rope-like material. Thus, it may be expected the behaviors towards the video would be similar for both crafts. My system, EmbodiAR, offers additional affordances for interaction which does not require the use of hands (voice commands and staring at buttons to select them). As the system is segmented, the video cannot run beyond the incremental steps, which prevents the video from continuing too far without interaction. Additionally, there are figures included with each video snippet so manipulating the video is not as expected.

Due to the prominent use of video as a learning resource, Chang et al. [10] explore how to better understand the design space within the how-to navigation. As the learners hands are often being used during the task, they investigated using voice as an input mechanism. Their methodology involved first understanding how people navigated how-to videos (using a think-aloud approach while watching videos). Following, they focused on understanding how people navigate how-to videos using basic voice commands. Then lastly, they utilized a Wizard-of-Oz experiment for a handcraft task (knitting). An interesting point of interest includes pace control, as users want to jump between steps from within the video. This aligns with other research as aspects like the video segmentation help users more easily control the flow of the learning material [32].

Ganier [25] explored how adults process pictures and text in procedural instructions and how they planned their actions. They had 120 students follow instructions as either pictures or text while doing another task concurrently as an interference task (e.g., remember words via audio while following the pictorial instructions). Their findings suggest even if learners understand the process from the pictures, they do not carry out the inferential processes until the text or other elements in the pictures (arrows, etc.) lead them to. They suggest the combination of text and pictures support learner understanding. This informs my research as it is expected the use of matching textual/audio descriptions with pictorial instructions will be helpful.

2.3.5 Capturing Hand-based Embodied Knowledge

Flanagan and Fraietta [21] use technology to help record, analyze, and archive the hand gestures of master craftspeople in the context of embroidery in an ethnic minority in China. Their motivation is to capture enough data to re-enact the traditional techniques in the case that the master craftsperson is unable to teach anymore. They use the combination of leap motion, PixyCams and videos to record a stream of hand movements from the craftsperson. They motivate the use of hand tracking technologies as they will not impede the craftsperson from using their hands (avoiding hand tracking gloves). This video is then fed into a machine learning algorithm designed to detect gestures of the hand movements involved with doing the stitch. The machine learning algorithm is coupled with a video player so the state of the stitch controls the playback from the video. While they do not contain an evaluation of their prototype, their work raises questions such as "what can be learnt about teaching through embodied experiential practices and critical processes of making" [21]. My evaluation could provide insights on their question as my work uses a similar form of recorded hand tracking data. However mine uses it as a basis for visualization, whereas theirs uses it for feedback and video player control.

Baurley et al. [2] explore capturing the embodied knowledge based in the context of cooking using digitally-networked utensils. These digital utensils would measure and record the information based on how one's hands interacted with it. They conducted a series of workshops with varying prototypes to explore and validate designs for capturing embodied knowledge while cooking. Notably, as seen in Figure 2.4 one prototype featured a glove with approximate measurements which captured quantities and servings of ingredients held in the hand. Although not explored in this thesis, a similar application could be used in craft or beadwork as methods for collecting embodied knowledge. This could involve the use of digital tools such as digital needle or thread, or accessories such as a glove.

Mo et al. [61] propose *Gesture Knitter*, an application that breaks down complex hand gestures into primitives. Ultimately, Gesture Knitter uses machine learning to generate and understand hand gestures, and is able to achieve high recognition with a low amount of training data. It is designed to create hand gestures for headworn mixed reality applications, which could include bead weaving or other handcraft. Similar to my research, they use the hand tracking capabilities from the HoloLens 2 [55]. Interestingly, they do not use all 25 of the joints provided by the hand tracker, only note that they use 18 joints with no further justification.

To visualize this embodied data, Li et al. [48] review approaches for visualizing motion capture data. In Figure 2.5, they visualize different techniques for motion cues which include: motion arrows, noise waves, and stroboscopic motion. While most of the reviewed systems cover whole body data, these techniques can be isolated to the hands, which offers interesting opportunities for instructing hand movement.

Figure 2.4: Glove to capture embodied data in cooking [2]

I explored utilizing such techniques in my early work, however moved away from directly guiding hand movement for bead weaving, which is further discussed later in the takeaways from my preliminary work.

2.4 Augmented Reality

2.4.1 AR Guidelines

Researchers in the field of AR have devised guidelines for working with AR in different aspects. These include but are not limited to: challenges to work with the medium, the design of virtual content, and how to interact with the user.

Merino et al. [52] conducted a systematic review of 458 papers on mixed and augmented reality (MR/AR) published in ISMAR, CHI, IEEEVR, and UIST over the

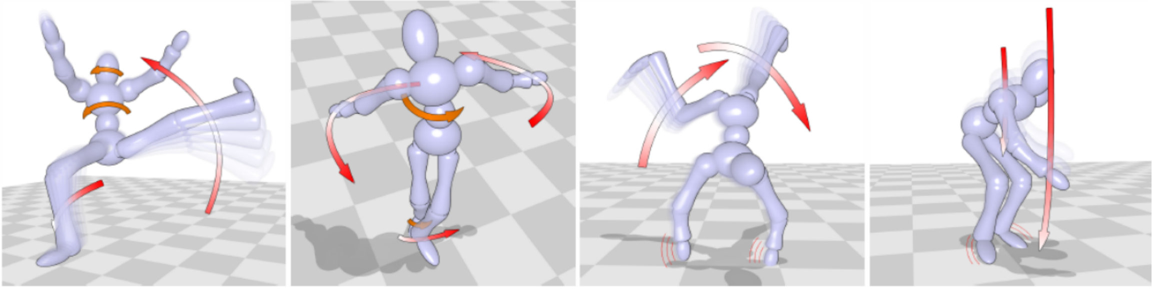

Figure 2.5: Motion cue examples: motion arrows, noise waves, and stroboscopic motion [48]

range 2009-2019. Their results found an increasing number of publications focused on MR/AR over the recent years. They note that MR/AR is a complex technology that even in laboratory based-studies it is difficult to test "higher-level cognition" [52] without being confounded by the flaws from the current MR/AR technologies. Factors such as the novelty of the medium and drawbacks (e.g., cumbersome to wear headset for long duration) could influence how participants feel about the aspects that are being studied. In the context of a comparative study, the effects of these drawbacks could overpower the effects of the conditions. Thus, it is important to control the AR medium to reduce the negative impacts (e.g., using AR headset across all conditions) which informed the study design for my research.

Krauß et al. [43] provide guidelines for collaborative AR/VR application design and development. There are numerous challenges involved including software and hardware capabilities and lack of development support which increases difficulty in creating a robust AR application. Marques and Costello [50] discuss the challenge of familiarizing new users to the medium of AR as most people have not experienced it yet. Furthermore, in a study investigating current challenges for mobile AR experiences in a museum, they found that visitors liked to choose their own pace for the experience. This indicates that it may be useful for users to choose their own pace as they get comfortable with this new medium.

Dabor et al. [14] present an AR UI design framework. They propose four key guidelines for an AR interface: novice and experts should be able to use it, users should be able to set their own pace and personalize their experience, the interface should be intuitive, and information should be in an easy-to-understand format (e.g., text should be concise and clear). I utilize these design guidelines for my system to provide a variety of interaction techniques that can be used quickly and let the participants choose their own pace.

Rolim et al. [65] survey visualizations and techniques to address the gap in AR design guidelines for instructions. They found from their sample of reviewed literature that most approaches are "are basically the same: information is presented using text, images, videos, 2D and 3D objects" [65]. They propose a design framework for AR: indicate movement, inform what to move/change, different attributes in the instructions should be visually different, feedback should be provided to users, and 3D instructions need to focus on overcoming issues with occlusion and distances. The approaches pursued for my research align with approaches from previous work, which grounds the AR learning materials. I utilize these design guidelines to indicate movement of the beads and hands, emphasize parts of what needs to be moved (e.g., user's hands, beads, or needle), and contrast the learning instructions.

2.5 Learning Applications for Augmented Reality

2.5.1 Learning Craft

There are similar systems which have been used to either teach activities focused on similar tasks or using similar technologies.

There has been some work on embedding AR visualizations within craft. Kang et al. [38] developed an AR application called *PrototypAR* which allows children to use virtual elements to extend paper craft. Furthermore, Edlin et al. [20] explore the role of AR in craft making, however, they find a lack of research within the scope of augmented reality and craft. They interview craftspeople about their making process, and construct an AR prototype to conduct an analysis with craftspeople to understand whether virtual AR content is aligned with their values towards craft. They find makers stressed the idea that what they want to make comes first, and the technique required to create it comes second. They recognized that this idea is vague and that the materials they work with shapes the ideas they are creating. Between traditional and digital makers, they found a disparity where traditional makers emphasised making something with their hands is embodied knowledge, whereas digital makers see working with their hands only as an option for interfacing with the materials. Additionally, from their initial interviews, “there was skepticism about the ability to purposefully incorporate AR - it was noted that video and audio can already supplement physical artefacts, and therefore AR was not necessary or needed” [20]. Following the interview they created a prototype which augments the created craft with virtual content as illustrated in Figure 2.6. The virtual content includes: 3D models, sounds, and a hand recording of the craft work in progress. Overall they found makers understood the augmented virtual content as part of the craft itself, treated the virtual content equally to the physical craft components, and most notably “none of the participants endorsed the hand-recording virtual content as especially informative or interesting” [20]. One of their participants suggested “either showing more ‘impressionistic’ recordings that are open to interpretation, or more precise recordings that can be used as a teaching tool rather than evoke an aesthetic response” [20]. There was an initial hesitancy towards the usefulness of AR partly due to their lack of familiarity with its capabilities, however, participants who viewed the AR prototype seemed accepting to the use of AR. Figure 2.6 displays the representation of hand joints (skeletal), which as mentioned was found via participant feedback to be not precise enough to be used as a teaching tool. This helped informed my research to explore a more precise life-like skinned mesh renderer of the virtual hands within the context of the steps.

Rosner et al. [66] explored the role of technology to enhance the dissemination of the handcraft process. They developed a system to record and playback the information from the knitting process which is embedded in the resulting craft. It records the yarn work through infrared sensors and infrared ink within the yarn, and maps it to data captured throughout the process of craft (e.g., photo, video, audio). The user is then able to view the data by viewing the mapped portions in the screen as shown in Figure 2.7. They initially used a field study with craftspeople to motivate their design and then provided two evaluations, where they iterated on the prototype. Their evaluations found participants used their system for “reflection, preservation, personal storytelling, and creative inspiration” [66]. Their evaluations suggest that their system has the potential to extend the social aspects of this form of handcraft. The implication of this work suggests how aspects of handcraft can be recorded and

Figure 2.6: AR block jewellery with augmented virtual content [20]

used to re-access the data from the crafting process. It is promising to see how participants were open to the recording and exploring of their work which would serve well to the use of technology to capture and render handcraft.

Handosa et al. [29] describe an approach for how to use a HoloLens 1 and Microsoft Kinect V2 [82] (an additional joint sensor) to support interactions within the context of training and skills development. While the HoloLens 2 now features hand tracking, some of the advanced gesture recognition can be done without additional sensors. While the approach may no longer be necessary, the takeaways of how the combination of sensor data could successfully capture interactions is still relevant. These takeaways can lend itself to the data capture approach being used in my data collection process.

Figure 2.7: Rendering of information mapped to aspects of the work generated from the handcraft process [66].

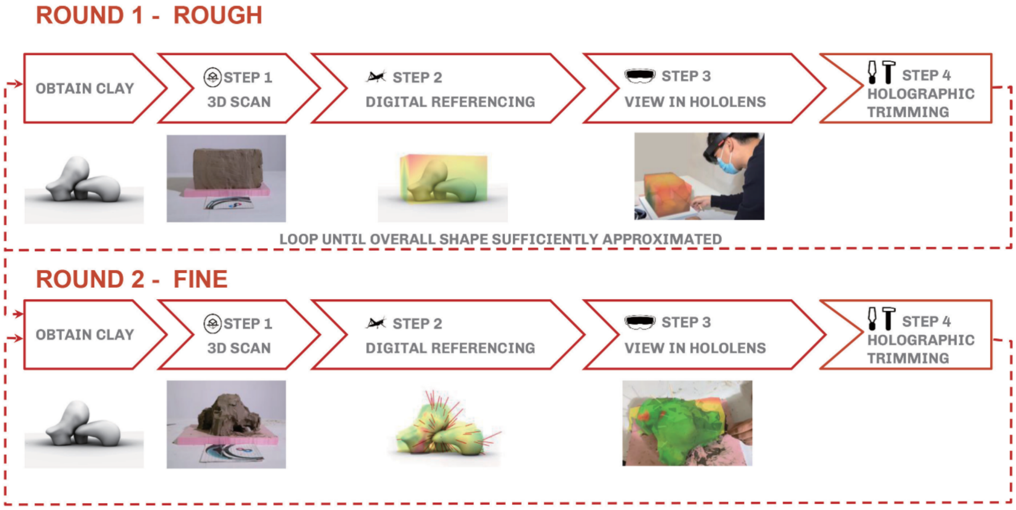

Figure 2.8: Workflow diagram of AR clay making guidance system [11].

Fong et al. [11] developed a headworn AR system to guide users in the hand clay-sculpting process. As illustrated in Figure 2.8, a digital reference model is overlaid within the material the user is working with. Then, the clay is color coordinated to show areas where the clay needs to be removed. Once a sufficient amount of clay is removed, a more detailed reference is overlaid to trim excess material. They evaluated the use of the system with amateur sculptors who were able to replicate the model with sufficient accuracy without prior training. By superimposing the digital model of what the result should look like, the user was able to infer spatial qualities regarding how to reach the desired result. While the system shows no indication of how sculptors should interact with the clay using their tools, the tool was sufficient for them to determine their own interactions. This influenced the design of the placement of the AR learning materials, to superimpose the AR learning materials at the area of work. In addition, their highlighted guidance mechanism influenced the guidance mechanism in the AR learning materials for guiding the stringing and threading actions.

2.5.2 Learning with Hand-based Tasks

There is more literature outside of craft which focuses on learning with users hands using AR. This includes tasks such as manual assembly.

Manual Assembly

Gupta et al. [28] address how to include the context of the real world by designing a real-time system for authoring and guiding Duplo Lego (essentially large Lego[1]) assembly. In their application, a user can work with Duplo Lego to build a model using visual feedback on a monitor. This system allows for recording and replaying of data for building the model and comparing that with traditional Lego instruction sets. They performed a user study (n=16) which compared their AR model with a static 3D figural based representation. Their results suggest that dynamically updating the pose of the virtual model to correspond with the real model can improve speed and accuracy. One noted limitation is this method requires large trackable objects (i.e., where regular sized beads are too small for tracking in this approach), I instead allow the virtual model of the 3D beads to be pivoted by the hand at the area of work. While this system provides context for active work, the visual feedback is disjoint from the model by projecting a virtual block model on a monitor instead of on the physical block model the user is actively working with, and thus the user has to work with two models (the real and virtual) to proceed with the task. My research incorporates the aspect of visual feedback, and explores the placement of the learning model. One placement is similarly disjoint positioned like on a screen, whereas another placement at the place of work where the user is working.

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[1] Duplo Lego https://www.lego.com/en-ca/themes/duplo

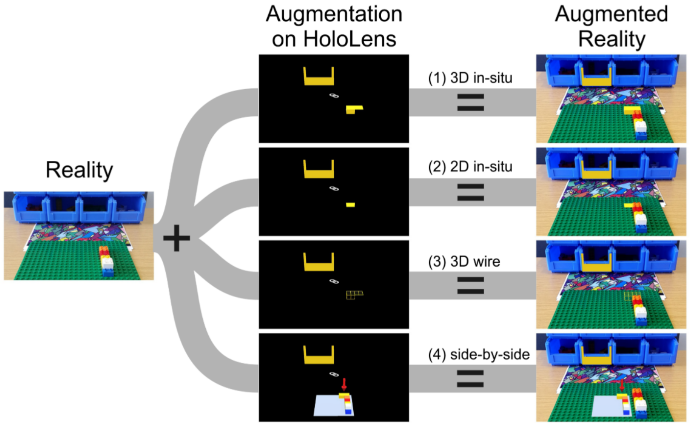


Figure 2.9: Different augmentation techniques of 3D and 2D representations of in-situ or side-by-side [5]

More recently, Blattgerste et al. [5] explore a combination of side-by-side or in-situ augmentation alongside 3D concrete, 3D abstract and 2D AR visualizations. They find in-situ instructions on state-of-the-art headworn AR outperform side-by-side instructions in terms of errors made, task completion time, and perceived task load. They note their results contrast past experiments [41], where side-by-side instructions had outperformed in-situ instructions. As shown in Figure 2.9, the comparison of side-by-side and in-situ are within the same frame of reference, however, are either at the place of work or neighboring it. As there are some mixed results regarding which positioning is more effective for learning, this still leaves room for exploration. My research further explores the positioning of AR learning materials, where they are positioned both in-situ and side-by-side close to the area of work versus off to the side.

Two other gesture visualizations focus on augmenting the model itself, in this case, the model is the person. Clarke et al. [12] propose *Reactive Video*, which uses recordings of body movements in sync with an exercise video, such that users can exercise in sync with the video based on their own body movements. While they did not formally conduct a study, they received feedback from visitors who used Reactive Video at their research lab. An interesting insight was that their users tend to mirror the instructor, which could suggest user's may learn by mimicking the shown movements. This could suggest users may try to mimic the hand movements of a bead weaver completing the same stitch. Jégo et al. [37] developed a real-time gesture visualization which visualizes the movement of hand gestures. It captures the direction and speed of the gestures in a generic way; however, unlike Reactive Video, it is not used as a method for teaching gestures. Instead, it is used to understand how people move their hands (e.g., understanding how people communicate with their hands in the field of linguistics). A similar form of visualization was utilized in my research for visualizing the path taken by the needle.

Werrlich et al. [79] compared HMD-based and paper-based training for the task of assembly training. They found "participants perform significantly faster and significantly worse using paper-based instructions" [79] in addition to trainees preferring the HMD-based learning. They provide a study design similar to that described in my thesis with 30 participants using established questionnaires such as the system usability scale (SUS) and NASA Task Load Index (NASA-TLX).

Jasche et al. [36] performed a comparative study to identify the influence of visualization types on user performance for setting up machines. They conducted a literature analysis to reveal many existing studies which evaluate the use of AR for manual assembly and maintenance tasks. These studies usually compared their AR system to traditional paper-based and mentor-based instructions. Similarly, another focus is on comparing AR-based instructions to other forms of hardware, and "only a few studies compare different visualization types for instructions using the same AR hardware type" [36]. In my research, I focus on this identified gap where I compare traditional materials within the medium of AR. Moreover, they conducted a user study using different forms of visualization (abstract and concrete 3D models), additional learning resources (videos or none), and using paper-based instructions as a baseline. The participants were given a tutorial, did a task on their own, answered a questionnaire (including NASA-TLX and SUS), and then closed with a semi-structured interview. They found concrete AR visualizations are more appropriate than abstract and that adding videos as an additional learning resource does not have a negative impact on execution time. Thus, I utilized these insights in the design of my AR visualizations, where I have each of my visualizations as concrete.

Lee et al. [47] address how to enhance first person task instructions by using an AR visualization of spatial cues in the context of operating or maintaining equipment

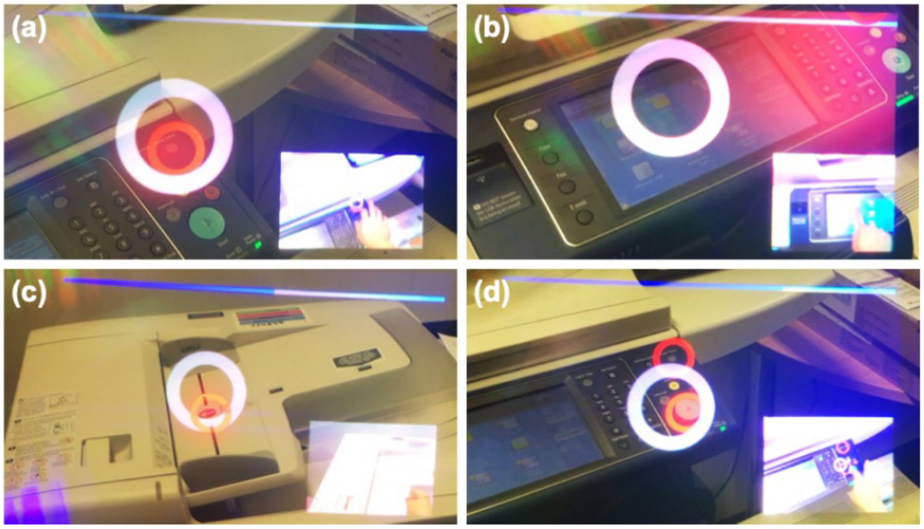


Figure 2.10: AR Tips: A use case of how to use a copy machine [47]

in a work place. They found a lack of research in combining AR cues with instructional videos. They implemented a prototype called AR Tips (as shown in Figure 2.10), which allows users to capture and render augmented instructional videos on a headworn AR device. They conducted a user study (n=18) to evaluate the benefit of their approach and found users can better understand the instructions, perform the task with fewer errors in less time, and maintain a low cognitive load with the use of augmented spatial cues. Their work suggests that an AR visualization for guiding users to regions of interest in addition to videos are helpful ways of learning tasks. While the AR component may be targeted towards guiding the user rather than teaching the user, there are some relevant findings on integrating instructions within AR. These include the participant's desire for more structure within the instructions, "such as dividing the video into subsections so that users can jump between them and better understand the task progress" [47]. This informed my design to segment the instructions for learning a bead weaving pattern.

Yamaguchi et al. [86] created an AR assembly system shown in Figure 2.11. This uses a 3D model with snippets of video clips that provide additional details including tools and complex motions. Their pipeline allows for the instruction to be generated from a 2D video and 3D CAD model as an input to their system. Their AR visualization followed established guidelines which includes using "step-by-step instructions, animations and free viewpoint changes to reduce a user's cognitive load" [86]. They

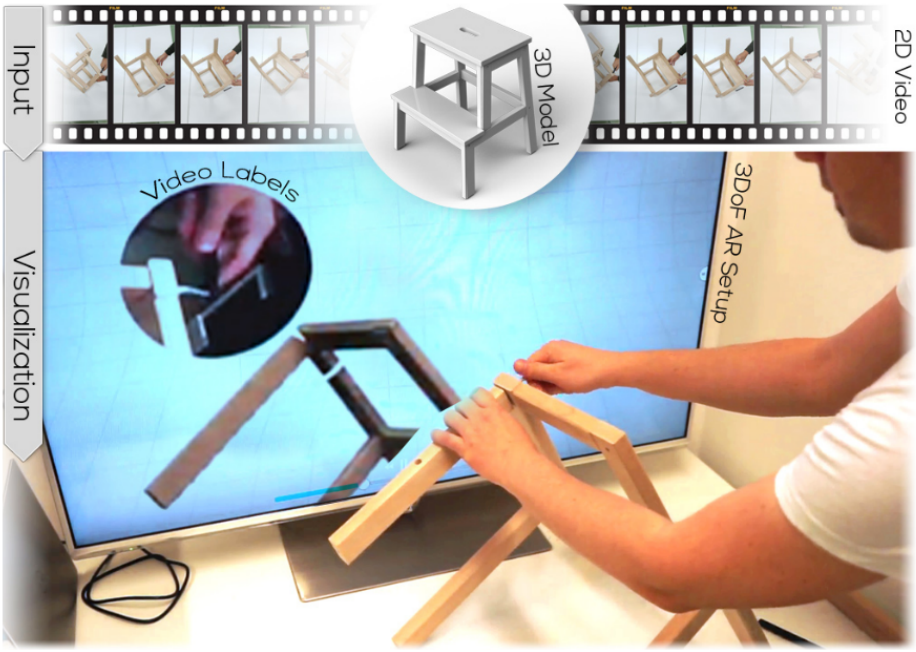


Figure 2.11: AR assembly system utilizing 3D model of work and video annotations [86]

evaluated their design by conducting a within-subject study where participants used either the AR system or a traditional video. An interesting note within the design is for the traditional video it did not automatically pause between assembly steps whereas in the AR system it did. Their results were supportive of previous research [40] where "users performed better when videos were automatically pausing between steps" [86] such that the user can control their own pace. They indicate future research "should isolate the effect of instruction segmentation for videos on the task performance when compared to the AR mirror system" [86]. Regarding the effectiveness of the AR visualization, they found the AR condition reduced mental effort due to the lack of occlusion. By having multiple viewpoints of the work, the task was not occluded by the hands or tools of the video's instructor.

The AR techniques studied have shown improved learning performance for assembly tasks. Büttner et al. [8] explore the training efficiency of paper-based and trainer-based learning materials over a longer span of time (i.e., 24 hours). They found no significant difference in training efficiency between AR-based and paper-based learning, however, AR-based reliably prevented systematic error due to the immediate feedback. However, "once an assembly task is properly trained, there are no differences in the long-term recall precision, regardless of the training method" [8]. Thus, they suggest the ability to provide immediate feedback in AR is beneficial over paper-based traditional materials, however, trainer-based learning is still most efficient.

2.6 Handcraft Applications using non-AR Mediums

2.6.1 Virtual Reality

VR is a similar medium to AR, however there are some key distinctions. Rupprecht et al. [67] describe VR: "visual interaction environments make possible the sensation of being physically present in a nonphysical world". Essentially, VR renders virtual objects in a virtual environment whereas AR renders virtual objects in the real world. However, both AR and VR overlay virtual objects in physical space. As they are similar, VR has been a choice for handcraft applications as well. Additionally, while some research contributions have been targeted towards AR, it is not uncommon for systems to be evaluated within VR first due to technical limitations and similarity of the mediums [51, 87].

Yu et al. [87] investigate how MR can be used to guide body motions. They conducted three controlled user studies using VR devices as they did not have the same technical limitations as AR devices. They find in their study that using a first-person view for motion guidance leads to better performance than either third-person or mirror-person for following motion and time taken. This informs my research as it indicates that following virtual guidance (such as digital hand movements) would be more effective from a first-person perspective.

Huang et al. [34] compared AR and VR for knowledge retention in the context of science knowledge. Their results suggest VR is "more immersive and engaging" [34] due to the spatial presence, whereas AR is more effective for conveying audio-based learning information due to the increased cognitive demand with immersive VR experiences. They had 109 participants use an AR/VR application (depending on condition) for five minutes to visually see and hear all the content presented in the application. For the context of bead weaving, the insight that AR is more effective conveying audio-based learning information than VR supported my design to utilize audio-based learning instruction.

Brondi et al. present [6] a general architecture for Mixed Reality applications with a focus on intangible knowledge. They provide two case studies of developed applications for teaching craft knowledge (weaving and printmaking). Both techniques use VR with differing interaction strategies albeit with no user study for comparison within their work. The proposed system builds on an in-house VR development framework called *XVR technology*. Focusing primarily on VR displays, the system renders hands realistically while watching either a depth video or animated avatar as reference. One strategy involves using cyber gloves, which capture the user's hands and renders them in virtual space, so they can interact with the virtual loom. The second strategy uses recorded depth video, which is rendered in VR. The latter technique provides the context of what the recording user was working with in 3D space, which is highly important for these visualizations. However, as these applications utilize VR the user does not have the context for the material in their hands due to a screen blocking their eyes. Thus, this work provides useful design guidelines for building a handcraft visualization, however, my system utilizes AR to include the active context of the user's work.

Building on the XVR technology presented by Brondi et al. [6], Carrozzino et al. [9] present *AMICA VR*, a system to disseminate craft knowledge in the context of printmaking. They utilize the immersion from VR to place users in the presence of an expert in a virtual environment. They argue "the easiest and more efficient way to transfer practical skills consists in observing and emulating an experienced user" [9]. The system generated from this work allows viewing skills but users do not attempt to reproduce it themselves in VR as there is no form of evaluation or comparison presented. In my research, participants reproduce the actions shown to them.

Hansen [30] shows that the use of VR has extended the way of crafting and created new possibilities in the context of ceramic crafts. They find VR techniques have opened up new ways of making that builds on traditional craft-based knowledge rooted in skills. They consider an explorative design approach that involved creating a model in VR and using a 3D printer to fabricate the clay craft. This work demonstrates the ability to utilize the medium as a tool to create craftwork rather than only strictly for learning and preserving. The process of using AR or VR as a tool to create craftwork is not further explored in this thesis.

Fu et al. [23] propose *RestoreVR* which is an interactive VR system that engages user in a mural restoration. By conducting a user study (n=30), they compared their system against the traditional methods (video and non-interactive web-based VR system utilizing audio and panoramic images) on the effectiveness of conveying tangible cultural heritage. They found the interactive system allowed for the captured embodied knowledge to be more engaging and convey knowledge that is tacit, whereas the traditional methods conveyed knowledge that was more factual. Although this is for VR, this helps align expectations that 3D virtual hands in AR would be able to convey more tacit knowledge on how the hands move in comparison to traditional methods.

Xiao et al. [85] explored how to teach hand movements using a variety of hand visualizations in VR as shown in Figure 2.12. They used a between-subjects design with eight participants per condition to evaluate a drawing task using different hand visualizers. They found a relationship between performance and realism of the hand, such that the more realistic version had the greatest performance. This aligns with other research [20] that a more realistic hand renderer would be more suitable for learning.

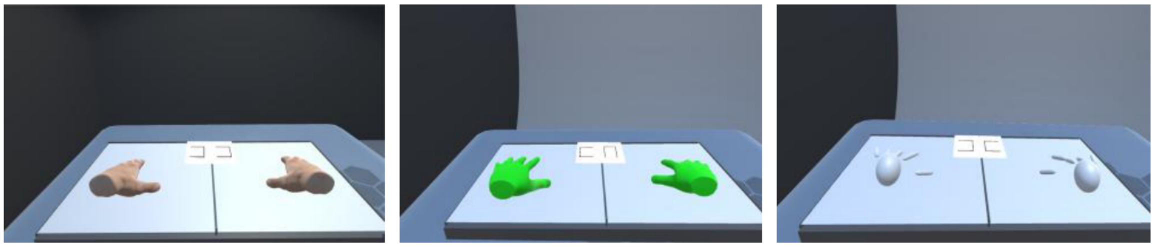


Figure 2.12: Virtual hand visualizations (in decreasing realism from left to right) [85]

2.6.2 Tangible Computing

Golsteijn et al. [27] combine the creative practices of crafting and making with digital technologies. They created *Materialise*, which is a building set that allows the inclusion of digital images and audio files in tangible connectable building blocks. By using this set in four creative workshops, one of their findings related to the craft process is to provide both physical and virtual materials and to keep the interaction techniques between them closely coupled and similar to each other for an optimal cohesion between the resources (i.e., to interact with the physical block is similar to the virtual block). In the context of my research, this links to keeping the virtual learning material and physical materials similar and closely coupled so it could be easier for users to closely relate their physical work with the virtual content. For example, the virtual 3D bead model to be interacted with similarly to the user's own beadwork.

Nitsche and Weisling [63] cover how craft has emerged as an important topic within HCI and provide a "critical re-positioning of craft to interaction design". By using three short example cases, they elicit an important debate on what is considered craft when traditional materials get intertwined with computing. For example, tangible devices may use craft as a reference, but not be practicing craft by definition. While this work poses interesting questions regarding how craft can intertwine with computing technologies, it is not further explored in this thesis.

2.7 Summary

Overall, my literature review search process exposed state-of-the-art systems and current literature related to my research, assisting in verifying the contribution of my research is novel. Bead weaving has deep cultural roots, however, there is still an importance to safeguard and explore teaching of bead weaving skills. The current state of learning bead weaving for independent learning resources includes: videos, figures, text, and audio-based learning instructions. Hand-based embodied knowledge is captured by collected joint data in the hands, which can be used for visualizations of the hands.

Current state-of-the-art AR capabilities from the HoloLens 2 allows for a rich exploration into embodied learning, which has not been readily available in the past. There are a selection of AR systems, which help embed craft into technology, however there is a lack of research on the evaluation of teaching bead weaving and handcraft skills within AR.

Chapter 3

Preliminary Work

3.1 Introduction

For my preliminary work, I introduce the interdisciplinary project that I worked on throughout my degree. It helps serve as a timeline of the work I have done and how it informed my research. Following, I cover two precursory applications I developed during my project, which have informed and served as foundational software components for my research.

3.2 Gesture and Form

Throughout my research, I was part of the Gesture and Form project which helped form and structure my thesis. Gesture and Form is an interdisciplinary project between architectural design and technology, cultural anthropology and material culture studies, and HCI to investigate the integration of AR with handcraft and educational design.

I joined the project in November 2020 and began with HoloLens 2 development with a longer term goal to explore different AR-based approaches and see what they can offer for handcraft projects. My first exploration involved learning about the Mixed Reality Toolkit (MRTK) in Unity by learning design guidelines and implementation requirements. I worked on deploying sample applications on the HoloLens 2 alongside weekly readings to familiarize myself with the deployment target and cross-disciplinary environment respectively. I became familiar with the HoloLens 2, MRTK, and the project dynamics. More details on the use of AR is described in the following section.

Following familiarization with the technology and the context of the project, my first milestone was to develop an application to record embodied hand movements. I describe the application in greater detail in the following section, but essentially we wanted to record and save the hand movements of a bead weaver while they work. I developed a system called the *Hand Tracking Recorder* which recorded the hand movements and exported them to a JSON file.

Throughout the development process, I gained insight into the development of bead weaving applications by working with the research assistants from other disciplines. For example, I asked one research assistant from the material culture studies what tools they used to learn bead weaving. They reported that they struggled with instructional guides (step-by-step books with images and words under the image) as their work did not seem to come out properly. They found YouTube videos that focused on the hands helpful, and then referenced instructional guides later. They also felt more confident with someone else working with them, and noted that voice and annotation would help with their learning. These insights were combined with those from the literature review.

For my second project, my goal was to create an application which could visualize the hand movements from the recorded bead weaver and use it to guide the hands from the user that is currently bead weaving. I was able to develop a system called the *Hand Tracking Visualizer* which would detect the hands of the current user and guide their hands to follow a set of recorded virtual hands.

As a team we reflected on the Hand Tracking Visualizer through both video-based demos during our weekly meetings and software testing sessions following the system implementation. We had concerns regarding the usability of the visualizer as a teaching tool which are further described in the reflection of the Hand Tracking Visualizer.

My following task was to take the visualizer I created and implement additional teaching capabilities alongside a comparison to traditional bead weaving learning materials for the basis of my study. This resulted in my third application *EmbodiAR* for my research, which is used to teach bead weaving stitches using AR. I iterated on the implementation of EmbodiAR with feedback from the team members, an expert bead weaver, and a pilot study where the feedback implications are described later in the EmbodiAR section. EmbodiAR was used as a tool in my evaluation and was also used as an educational resource for a bead weaving workshop held by other members in Gesture and Form. My role for the workshop consisted of continuous support and integrating changes as needed (e.g., data collection for the scope of the workshop). The implications of the workshop are later described as current work in the discussion.

3.3 AR Development

3.3.1 Current AR Capabilities

The HoloLens 2 [55] is an untethered headworn AR headset that is featured in numerous recent studies [61, 87, 47]. The HoloLens 2 features a see-through holographic display [55], allowing the user to see virtual holograms while seeing the real world. This is a critical reason AR was selected as the medium for my work, as the user can see their own hands and beads while they use the system.

Holograms can either be placed spatially or fixed to the display, and can feature 3D or 2D representations (e.g., a 3D holographic chair on the ground in front of you, or a 2D health bar fixed at the top right of your vision). The display works using additive light [81], where the display renders light over what the user is seeing, such that the headset cannot render black colors (i.e., the absence of light) instead the black objects would be invisible. I utilized a combination of 2D and 3D representations and rendered both spatially and fixed to the display, referencing the HoloLens 2 development guidelines [54].

The HoloLens 2 can also understand aspects of the user's body. This includes:

1. *Hand tracking*: The HoloLens 2 is capable of discerning the positions and rotations of each joint in each of the user's hands. This can be used in a multitude of ways, including but not limited to interaction (e.g., touching 3D buttons), anchoring objects on the hands, understanding the hand movements, and customized gesture control.

2. *Eye tracking*: The HoloLens 2 can detect where the user's eyes are looking. This can be used to calculate where the user is looking at what time and can be used for interaction (e.g., dwelling their eyesight on a button to select it), or understanding (e.g., recording which UI element the eyes look at most).

3. *Voice recognition*: The HoloLens 2 can recognize the voice from a user. This can be used for interaction (voice commands), dictation, etcetra.

I utilized every interaction element from the aforementioned body understanding capabilities in my research to capitalize on the current state-of-the-art AR capabilities. Additionally, I used hand tracking to place objects near the user's place of work, and for direct manipulation of the model.

The HoloLens 2 is capable of environment understanding [55], where the device is able to track its own position over time. Additionally, while it moves it is capable of building an understanding of the walls and surfaces by crafting a "real-time environment mesh" [55]. I did not utilize these capabilities to their full extent as for bead weaving the user's position is static in space (i.e., sitting in a chair), thus not requiring extensive spatial mapping. Furthermore, the environment understanding is insufficient for tracking the beadwork due to the bead's small size and dynamic movements. I did however utilize a portion of the spatial understanding to position the virtual holograms in space. I also used the Mixed Reality Capture [53] for the purposes of data logging, which allows for the HoloLens 2 to capture video and pictures from the camera sensors.

3.3.2 AR Development Environment

Ashtari et al. [1] interviewed AR/VR developers and found that there are two main categories of development tools. One are less developed tools created in startups or in research, but these have often small use cases and a small community with limited help. Whereas the second more popular class was "professional, feature-rich frames, such as Unity" [1].

Unity [76] is a popular cross-platform game engine which supports both 3D and 2D applications, and a varying number of AR devices. In this case, Unity supports the Universal Windows Platform (UWP) [59] which allows me to deploy an AR application to the HoloLens 2. Unity features a *scene*-based system. Therefore, the resulting application is composed of a collection of scenes and a scene is a collection of game objects and associated scripts which have behaviors that start running once the scene loads.

To develop an AR application in Unity, it needs some form of AR toolkit or framework such as ARKit [35] (for mobile iOS AR), ARCore [17] (for mobile Android AR), or ARFoundation [78] (cross-platform Unity AR framework). To develop a

HoloLens 2 application in Unity, I used the MRTK which is a toolkit that includes the foundational elements for controlling the HoloLens 2 within a Unity scene. It also provides pre-fabricated virtual elements for faster prototyping which I used as foundational pieces within my applications. Finally, it acts as an interface between the HoloLens 2 and the Unity application and allows for additional extension points to utilize the HoloLens 2's capabilities.

3.4 Hand Tracking Recorder

The Hand Tracking Recorder was created in Unity with MRTK. The application employs several visualization techniques, which informed the visualization component in the Hand Tracking Visualizer and EmbodiAR. The app collects hand tracking data from the HoloLens 2 and stores it in a JSON file format.

3.4.1 Data Capture

To obtain hand data I first needed to develop a hand tracking recording application for the HoloLens 2. I created a recording application which accesses the hand joint data through the API provided by the MTRK.

This application allowed for some experimentation with HoloLens 2 development, specifically on accessing hand data, interacting with HoloLens 2 via voice commands, and building UI elements for the HoloLens 2. This development experience was helpful for incorporating features in the other HoloLens 2 applications.

Figure 3.1: Hand Tracking Recorder: tracking user's hands

As seen in Figure 3.1, the recorder features a heads-up display UI element for textual instructions on how to start recording. Additionally, two icons signify if the hands are being successfully tracked (green indicates it is successfully tracking the hands, and red indicates tracking was lost). Voice commands “Record” and “Stop” allow recordings to be controlled. Recordings are saved locally to the HoloLens 2 which can later be accessed by the device portal. The instructions update when recording as a blinking red recording icon appears. Once commanded to stop, the application saves the file and notifies the user once it has been saved.

3.4.2 Data Format

The hand tracking data is saved in a JSON format as a list of hand tracking frames. Each frame contains a timestamp (relative to start of application), offset from the camera position, and two lists of joint poses (one list for each hand). The data format went through multiple iterations (utilizing smaller data structures) to minimize the size requirements. Additionally, it previously contained the offset for right and left hand reference points (index finger) from the camera but that data point was redundant as it was the same value from the index finger.

3.4.3 Reflection

Throughout the project this software was used as a basis for recording hand movements, however, there were some limitations which have informed its design. There was susceptibility for lost tracking data if the user’s hand movements are out of frame or occluded for a long duration. While at first we encountered some notable tracking loss, we accommodated the HoloLens 2’s tracking ability by positioning the headset and hands in a manner to increase tracking quality, requiring the wearer to be mindful of lost frames. There was also susceptibility for corrupted data, such that a system interruption could cause large chunks of data to go missing. To reduce the risk, I switched to a stream-based recording style of writing the data as it is received as a raw text file. This was implemented for the study data collection and had an improved reliability for the scope of preparing my system and conducting my data analysis.

3.5 Hand Tracking Visualizer

I developed a 3D egocentric AR hand tracking visualizer as shown in Figure 3.2, which builds on the Hand Tracking Recorder. The visualizer renders a set of hands based on a dataset of recorded hand movement and the user is expected to follow it with their own hands. The system evaluates and guides the user's movement with respect to the recorded hand data. The system was used for generic hand tracking, but was designed to be tailored towards bead weaving. The system is described in more detail in Appendix C.

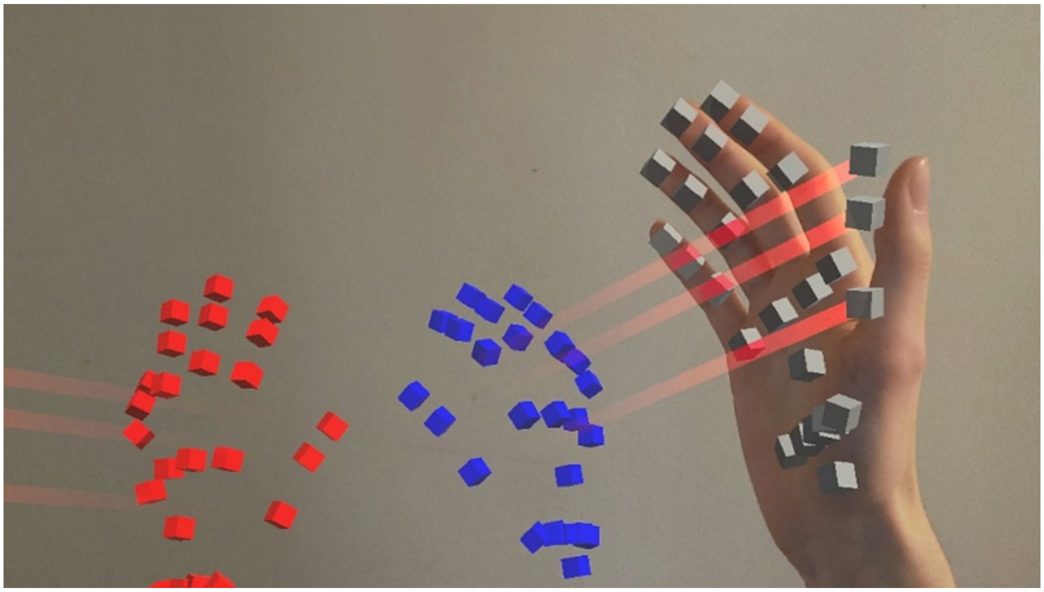


Figure 3.2: Hand Tracking Visualizer: visualizing user hands with indicator lines guiding joints to follow recorded hands

3.5.1 Reflection

There was no formal evaluation (either systems-based or human subjects) for the Hand Tracking Visualizer. However the development process and group feedback of the application provided insights for the development of EmbodiAR. I now describe why it felt appropriate to transfer and incorporate the visualizer into another system more structured to teach bead weaving patterns (i.e., EmbodiAR).

Hand Visualization

I learned that the data format was sufficient for capturing hand movements of a period of time as we were able to gain an understanding of how the hands were moving for the scope of my research.

As the digital hands consisted of numerous cubes representing the joints, there was an overload of visualizations so simpler visualizers such as a skinned mesh renderer was pursued for EmbodiAR. This aligned with the insights from the literature review to use more concrete realistic renderings for hand visualization [36, 20].

Hand Evaluation

The appropriateness of directly following the hand movements of seemed constraining for bead weaving in a way that it did not feel constructive to micromanage all the precise hand movements. While it could still be an interesting aspect to research, the focus of my research shifted exploring the use of the hand visualization as a guide rather than an instruction set. This decision reduced the need to scale the hands and was not maintained as evaluation was no longer used.

System Structure

The hand movements played as one continuous stream (like a video) and did not break down the steps. While the hand movements were understandable, it seemed it may have been difficult to correspond the bead weaving actions for the beadwork and that of the hand visualizer. As research had found segmenting video could help in following instructions [86, 47, 32, 10], this informed a structural change of the system to break down the steps to smaller segments. In addition to the need to improve context, audio-based and text-based learning instructions was included with the hand visualizer to provide further context on what is occurring at each step.

The interaction with the menus was primarily with touch, however, if the user's hands were occupied by the task, then the task would have to be interrupted to interact with the interface as found by Heinemann and Möller [32]. This suggests the need to integrate more interaction techniques which do not require hand interaction (such as voice or gaze).

3.6 Summary

I developed two precursory HoloLens 2 applications, which helped inform the development of my third application EmbodiAR, the final application from my research, which is used to teach bead weaving stitches using AR.

My first HoloLens 2 application, the Hand Tracking Recorder, allowed for a user to capture their hand movements and export them to a JSON file. The development of this app helped inform how to build a HoloLens 2 application and work with the hand tracking data.

My second application, the Hand Tracking Visualizer, can render the recorded and real-time hand tracking data, alongside evaluating a user's ability to follow the recorded data. Additionally, the system can guide the user to the next steps of the operation by using indicator lines. The development of this app helped inform how to build visualizations and menus for learning hand movements in AR.

Chapter 4

EmbodiAR

4.1 Introduction

EmbodiAR is a headworn AR application designed to teach bead weaving skills using an assortment of learning materials. A novice bead weaver would begin with the included tutorial to understand how the system works and learn bead weaving terminology pertaining to the instructions found in the system. Then they could learn one of two fundamental bead weaving stitch patterns (1-Bead Netting Stitch, 5-Bead Netting Stitch) using one of three configurations of learning materials (traditional materials, embodied AR materials, or static AR materials). I further elaborate the stitches and learning materials alongside the system design and its design decisions.

4.2 Bead Weaving Patterns

To teach bead weaving, a selection of bead weaving patterns were required. To compare the learning resources, participants were required to complete at least two trials so they have a basis of comparison. I could not use only one stitch between both trials, as the learning effect from the first trial to the second trial would be too great such that no further learning would have occurred. Additionally, I could not only use one stitch for the system as that could create a potential confound as learning may be dependent on the material. Thus, the bead weaving pattern was controlled by integrating two patterns into EmbodiAR.

With consultation from the handcraft-inclined members within the Gesture and Form project, two stitches were selected as suitable candidates for EmbodiAR: the *5-bead netting stitch* and *1-bead netting stitch* as illustrated in Figure 4.1. Both of these stitches have deep roots in history [74, 73]. However, they are broadly available foundational stitches, which do not belong to any specific culture. As the names suggest, they are similar forms of netting stitch. However, they feature similarities and differences that make these suitable for comparison, which I further justify shortly. It is important to note these stitches are seen as basic stitches with comparable difficulty [71], which make them suitable for novice bead weavers. As the 1-bead netting stitch is more commonly referred to as the *peyote* stitch, for clarity within this thesis I will use this to refer the 1-bead netting stitch as the **peyote stitch** and the 5-bead netting stitch as the **netting stitch**.

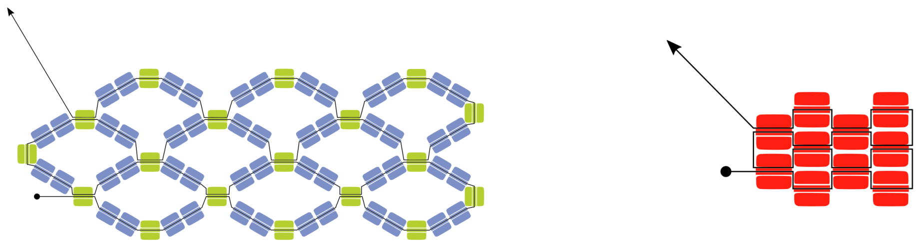


Figure 4.1: Selected bead stitch patterns. Left: netting stitch. Right: peyote stitch.

To outline the comparison between the stitches, I describe their similarities and differences. The steps to complete the stitches are broken down to a similar instruction set as shown in Table 4.1. Both stitches consist of threading and stringing actions, and both stitches are iteratively built in rows and create a net shape. The key differences are the number of beads and steps, and the resulting work it produces. For the netting stitch, it uses more beads, which produces a looser piece, whereas there is greater tension within the peyote stitch, which produces a more rigid structure. As the netting stitch has more complex steps, the design of our stitch has color-coded beads to assist in the identification of the beads which act as vertices in the net (as illustrated in Figure 4.1). We could have included a second set of colors to differentiate rows within the peyote stitch to maintain the factor of color differentiation, however, this may make the peyote stitch too easy with an increased similarity to the netting stitch. When testing different learning materials between these two stitches, there could be an increased learning effect between stitches themselves which is not preferred when comparing the effectiveness of the learning materials as it could produce a confound. I prioritized creating an equilibrium between the planned difficulty between the stitches instead of ensuring both instruction sets are as easy to understand as they could be. It is important to note that the operations listed in Table 4.1 are not the exact same

Table 4.1: Breakdown of stitch's elementary operations

5-Bead Netting Stitch *(Referred to as 'netting' stitch)*	**1-Bead Netting Stitch** *(Referred to as 'peyote' stitch)*
1. String 24 beads	1. String 5 beads
2. Thread through 1 bead	2. Thread through 1 bead
3. String 5 beads	3. String 1 bead
4. Thread through 1 bead	4. Thread through 1 bead
5. String 5 beads	5. String 1 bead
6. Thread through 1 bead	6. Thread through 1 bead
7. String 8 beads	*(looping back for new row)*
8. Thread through 1 bead	7. Repeat steps 3-7
(Looping back for new row)	
9. Repeat steps 2-9	

used for instructions, as building additional rows is helpful to provide more grounding before the instructions loop.

4.3 Learning Materials

I designed two distinct forms of learning materials: traditional-based learning materials and AR-based learning materials. Both of these learning materials are rendered within AR to reduce the impact of the headset being used to compare the experiences with the learning materials. Thus, this comparison focuses on the intrinsic qualities of the learning material formats to derive interesting comparisons on how AR can be used to support bead weaving and other similar handcraft tasks. It is important to note this is not a comparison between traditional materials in their typical format as seen in current use, as there would be too many variables for a fair comparison. These variables could include the fatigue from the headset, resolution of displays, etc.

4.3.1 Traditional learning materials

As derived in the literature review, I selected videos and figures as the traditional learning materials for learning bead weaving. The first step was to determine *which* videos and figures would be used to represent the traditional learning materials. The process I used was to determine a video that matched certain qualifications (details covered shortly), and then break it down to steps and create matching set of figures which matched a format of figures with their own qualifications.

Video

For the videos, I derived qualifications on selecting a craft video from Heinemann and Möller [32], which required video tutorials that are relatively popular for craft videos ($> 50,000$ views with a high like-to-dislike ratio and positive comments) and designed for novices with little-to-no prior knowledge. These videos needed to show how the stitch was completed and have a similar instruction form factor between them to avoid having the video format confounding with each other. However, there will usually be some slight differences between different human-based video tutorials. While we controlled the primary aspects of the video, there could be potential issues with mismatches between video quality, speed of weaver, et cetera. With consultation from the handcraft-inclined members within the Gesture and Form project, we selected the following videos:

- Netting: 'Stitches: Flat Vertical Netting' [83]
- Peyote: 'Peyote Stitch tutorial for beginners - Beadweaving with Svetlana Kunina' [46]

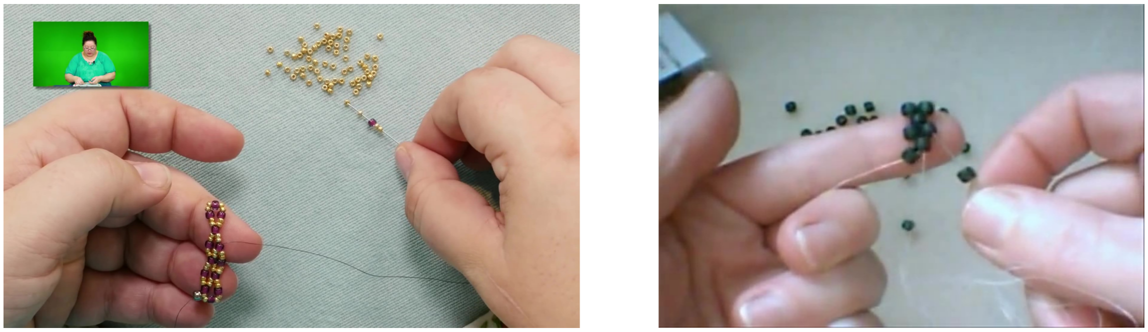
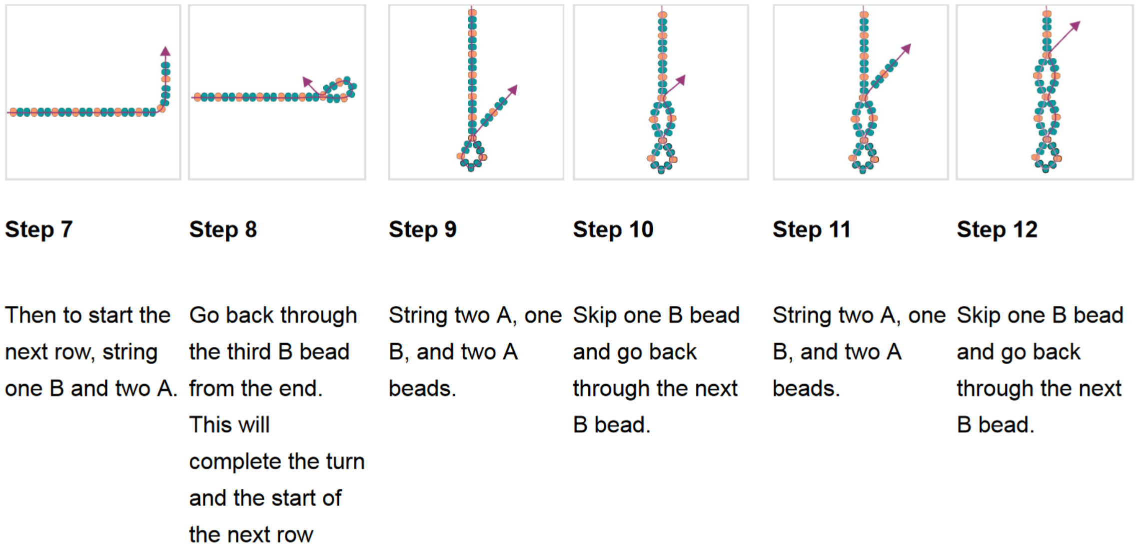


Figure 4.2: Snapshots from video learning material. Left: netting stitch. Right: peyote stitch.

A snapshot from both videos is pictured in Figure 4.2. The audio from the videos were removed as I already control the audio-based instructions which verbalize the context between all instructions, which reduces the differences between varying videos. This may have potential limitations regarding missing context aware audio-based instructions, however the step audio-based instruction aims to achieve a similar effect in a controlled manner.

Figures

To generate the figures, I first explored examples of figure-based learning materials for learning bead weaving to gain a deeper understanding on how figures are used. As shown as an example in Figure 4.3, figures were used in a series of steps to highlight how the beads and thread were positioned in a 2D representation. Then, I parsed the videos to find the states of the beadwork and created 2D figures for each representations. A preview of the generated figures are shown in Figure 4.1 with the full array of figures in Appendix D.



Step 7	**Step 8**	**Step 9**	**Step 10**	**Step 11**	**Step 12**
Then to start the next row, string one B and two A.	Go back through the third B bead from the end. This will complete the turn and the start of the next row	String two A, one B, and two A beads.	Skip one B bead and go back through the next B bead.	String two A, one B, and two A beads.	Skip one B bead and go back through the next B bead.

Figure 4.3: Snippet of *Basic Netting* 2D Figure from Fusion Beads [3]

4.3.2 AR learning materials

There are two primary AR visualizations within the AR learning materials: 3D virtual hands and a 3D bead model. The combination of the AR learning materials are designed to provide similar information shown from both the video and figures. As previously mentioned there are two options which relate to the AR learning materials. This primarily impacts the position of the learning materials by placing it by the place of work or to the side.

3D Virtual Hands

Similar to the hand tracking visualizer, I developed a set of three dimensional virtual hands, which visualize the hand movements of a craftsperson who has completed the stitch. I refer to these as *3D virtual hands*. These 3D virtual hands use the same data set format as the Hand Tracking Visualizer application.

From the hand tracking visualizer, I iterated on the design of the virtual hands yielding the result shown in Figure 4.4. The first major iteration was the conversion from the joint-based to mesh-based hand representation. The second major iteration was a decreased focus on the user's hand movements in relation to the recorded hand movements.

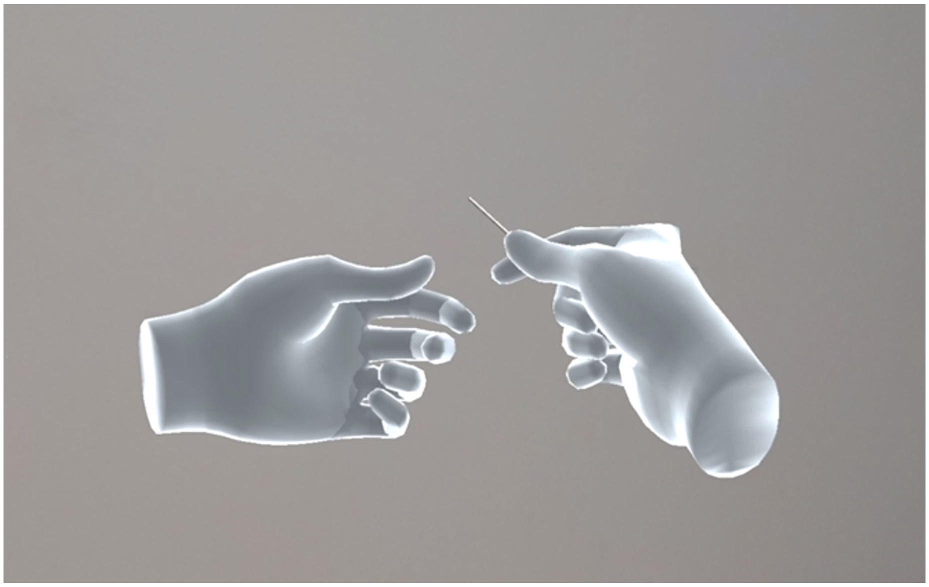


Figure 4.4: EmbodiAR: 3D virtual hands augmented with a tapestry needle on fingers

For the context of bead weaving, a virtual needle is anchored to the intersection of the thumb tip and index finger tip. For the stringing operations, a virtual bead appears on the needle and slides down the needle to the base as seen in Figure 4.5, where the bead will then be transferred to the 3D bead model. For the threading action, a purple trail is generated from the path of the tip of the needle for the set duration of the threading action as seen in Figure 4.8. This is to better indicate the path taken from the needle.

The virtual hands resemble the hands shown in the videos. One clear design difference is that the videos have the hands work with the beads, whereas for this

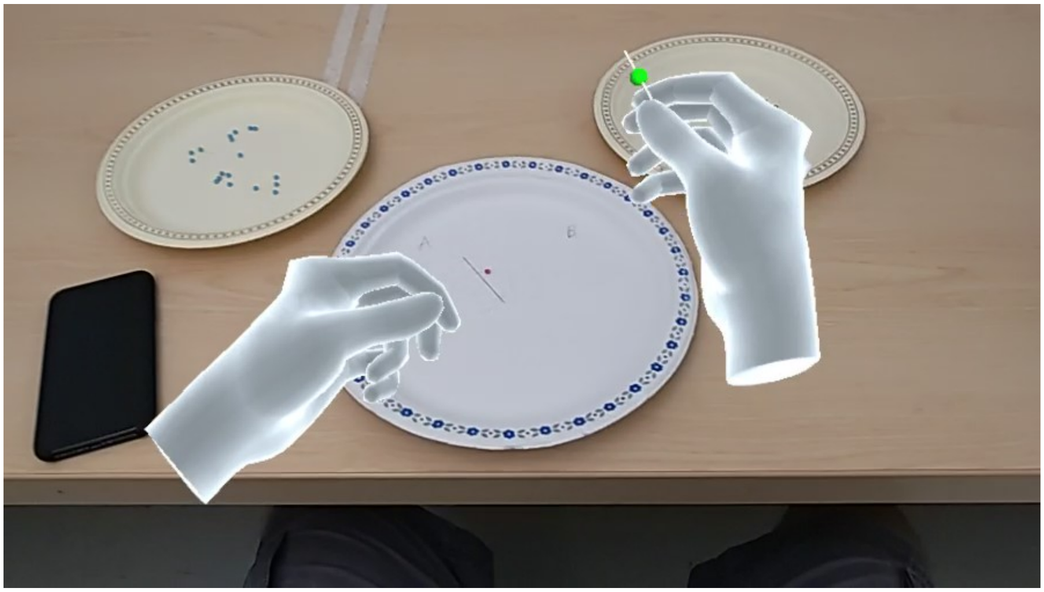


Figure 4.5: EmbodiAR: 3D virtual hands visualizing stringing action with bead sliding down needle

AR visualization the 3D beadwork is separated into its own representation. The comparison between these two learning materials explores the extent of the usefulness of the hand motions. Thus, a direct comparison between the 2D and 3D bead models and the 3D hands and video, is problematic with this design.

One challenge encountered during the development of these 3D virtual hands was generating the data sets for the bead weaving stitches. Currently, the hand visualizer interpolates the joints of the mesh renderer based on the recorded values, however, if there are large chunks of lost tracking frames (> 1 second), then the hand visualizer would disable rendering. Data smoothing could be used for minor chunks (< 1 second) to interpolate the nearest two values, but this strategy was not suitable for large chunks of missing data as the hand movements were unrepresentative of the actual action. In collaboration with one of the handcraft-inclined members within the Gesture and Form project, we generated data sets for the two stitches. They initially recorded the first round of data sets using both the hand tracking recorder and a video recording, however, this is when we encountered major chunks of missing data. Due to their limited availability, I reused portions of their hand recordings and mimicked their creation process based on the video and my experience with the stitches. Using this process, I filled in portions where there was missing data until it became representative of their hand movements while beading.

3D Bead Model

The 3D bead models as shown in Figure 4.6 are a new addition to EmbodiAR, which were added after the pilot study. While using only the hands, there was no context of the beads the hands were working with, so the 3D bead model was devised to combine a three dimensional version of the figure alongside context on how to perform the actions as resembled in the video. The base design of the bead model was derived partly from the exposure to varying aspects of design within Gesture and Form (e.g., deriving inspiration from the learning materials created by Architecture students who were learning bead weaving).

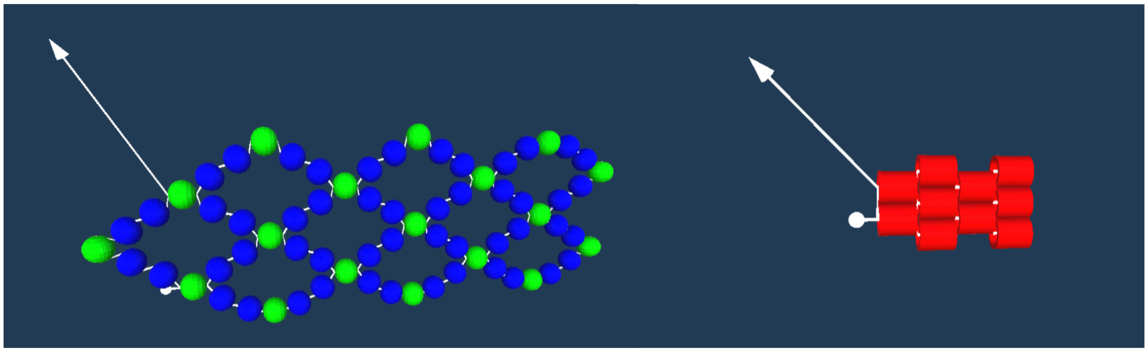


Figure 4.6: EmbodiAR: 3D bead models. Left: netting stitch. Right: peyote stitch

To generate the 3D bead models, a set of models were generated using the traditional figures as a baseline. The 3D bead model consists of 3D beads and a 3D thread. My research colleague generated the raw individual bead models in the modelling software Blender [22], as shown in Figure 4.7 and I assembled the beads to generate the bead models. To generate the thread, I created a script that automatically created a 3D line renderer with the vertices given from a list of sequential beads.

While representing the figure in a 3D format, there were additional indicators designed to integrate context that was represented in the video tutorials. For the stringing step, once the bead was done sliding down the needle in the hands, it would move to the end of the thread on the 3D model and slowly slide down into place. This was designed to convey the context of the moving beads. For the threading step, a purple line renderer was overlaid on the thread to highlight the path the needle took as

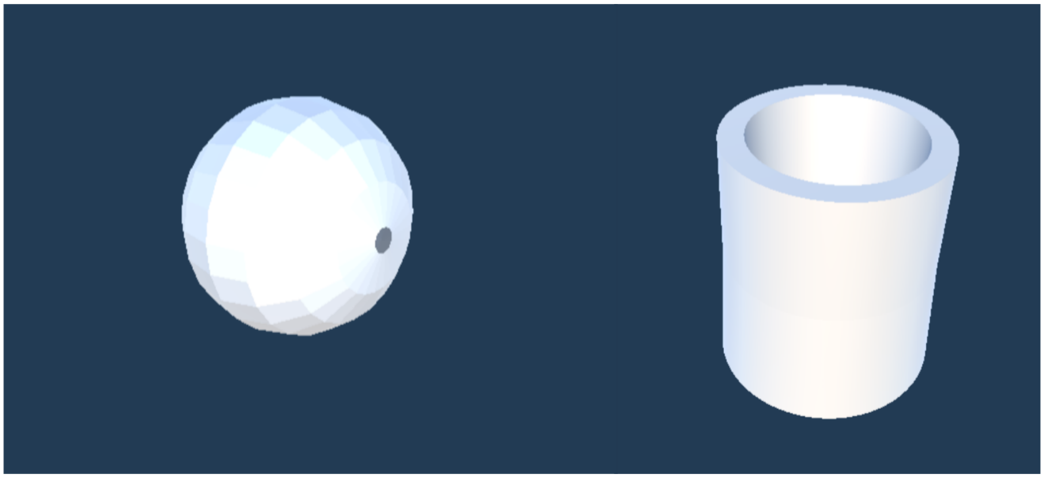


Figure 4.7: Raw bead models. Left: cylindrical bead. Right: seed bead.

shown in Figure 4.8. This purple line correlated with the same purple trail generated by the 3D virtual hands, as it was designed to connect the motion with the model.

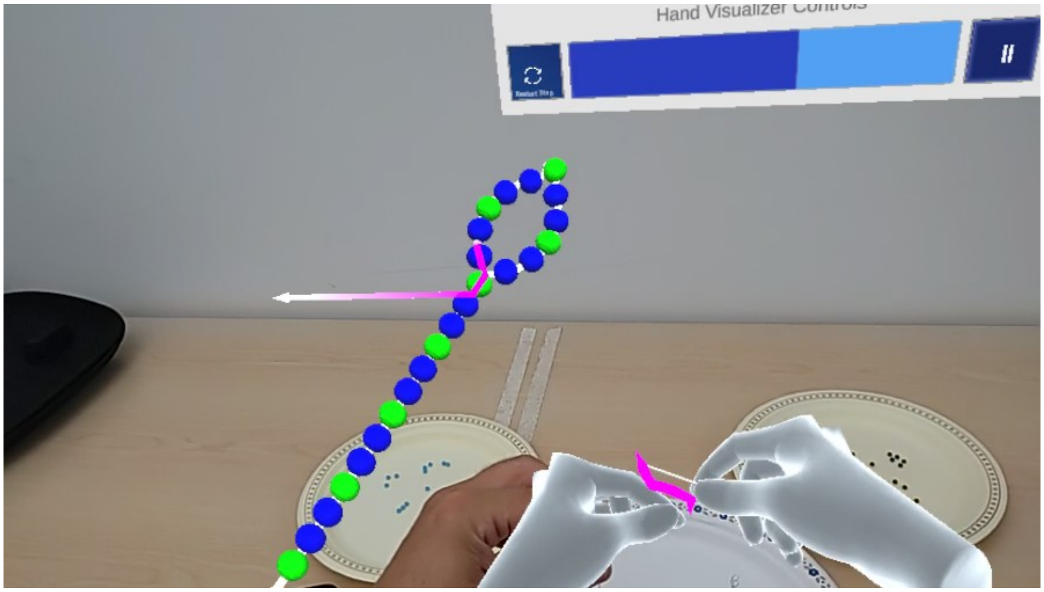


Figure 4.8: EmbodiAR: purple trail indicating threading action between hand movements and 3D bead model

Learning Material Placement

As mentioned in preliminary work, one attribute of AR is the ability to place 3D virtual content in the physical space. As 3D materials can also be rendered on 2D displays, it is useful to explore the spatial attributes of virtual object placement offered by AR. I developed two placement techniques: one where the 3D materials are positioned at the area of work, and another placement to the side which represented placements similar to a triple monitor setup [72].

For the placement of the virtual hands and the 3D bead model, we expect a combination of integrating the learning resources would be useful as the 3D bead model would add the context of the work and the hands would reflect the context of the action. However, I decided to separate them to closely examine the pros and cons of each approach which helps in comparing the two learning materials within the condition.

The embodied placement (i.e., placed at the area of work), is designed so the 3D bead model is anchored to the back of the non-dominant hand. Thus, the bead model could always be available with a quick glance away from their work. Additionally, users would be able to pivot the model by moving their hand. The 3D virtual hands are positioned where the hands are working. This may cause the hands to interfere with their working area, however this is necessary to provide the participant with the perspective as if it were their own hands. It could be hypothesized that the perspective of hands as if they were their own would increase understanding. The rationale behind this decision being that users do not need to reorient themselves to understand the hand movements as their own.

For the side-by-side placement, the learning materials are positioned such that the beadwork representation is to the left (e.g., 2D figure or 3D bead model) and the video representation is to the right (e.g., 2D video or 3D virtual hands). The positioning is reflective of traditional monitors to more closely resemble the perspective from traditional viewing mediums.

4.4 System Architecture

Now that I described the core learning materials, I will describe how the overall system is structured and used. I further describe the features and flow of the system in the following subsections.

As illustrated in Figure 4.9, the user opens EmbodiAR to find a title menu. From there the user can load either the tutorial or learning scene with the desired learning option. The tutorial and learning scene are based off a generic layout, which is populated by a learning settings configuration file. For research purposes, EmbodiAR is outfitted with data logging capabilities. When the stitch is completed, the user is able to return to the title menu.

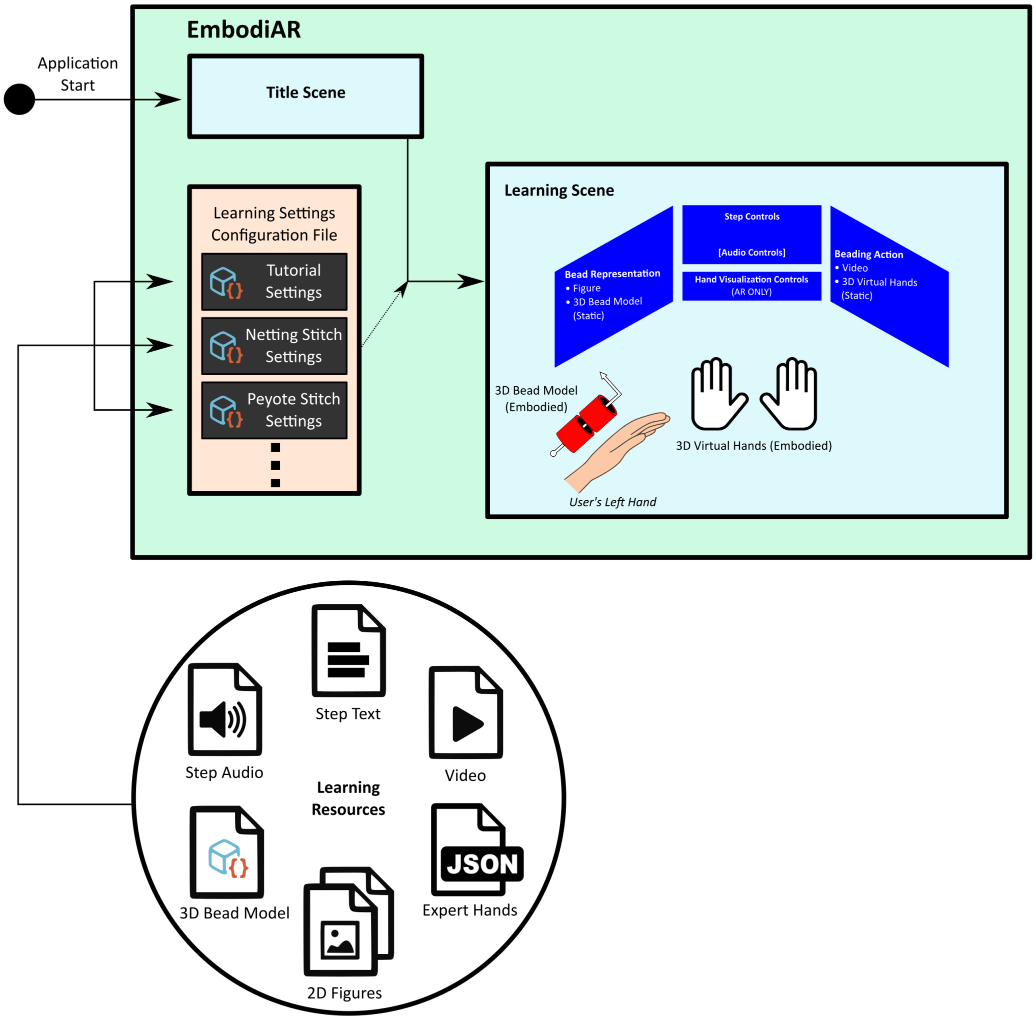


Figure 4.9: EmbodiAR: system architecture

4.5 EmbodiAR Menu

When the user opens EmbodiAR they are directed to the title menu as shown in Figure 4.10. The user can decide to do the tutorial, the netting stitch, or the peyote stitch. To do that, the user can press the holographic buttons with their index finger. Depending on the selected option on the right hand menu, the user can select the style of learning materials to use. To select the learning materials, users can either use voice commands or touch the buttons with their index finger.

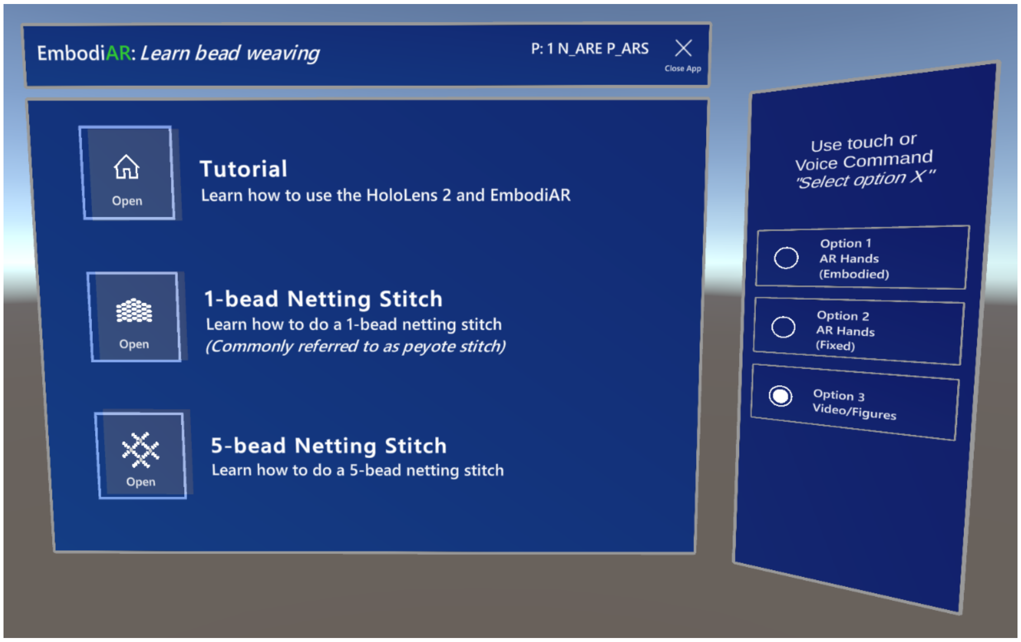


Figure 4.10: EmbodiAR: title menu

4.6 EmbodiAR Learning Scene

4.6.1 General Scene Layout

As mentioned, the learning scene features a general layout as shown in Figure 4.11.

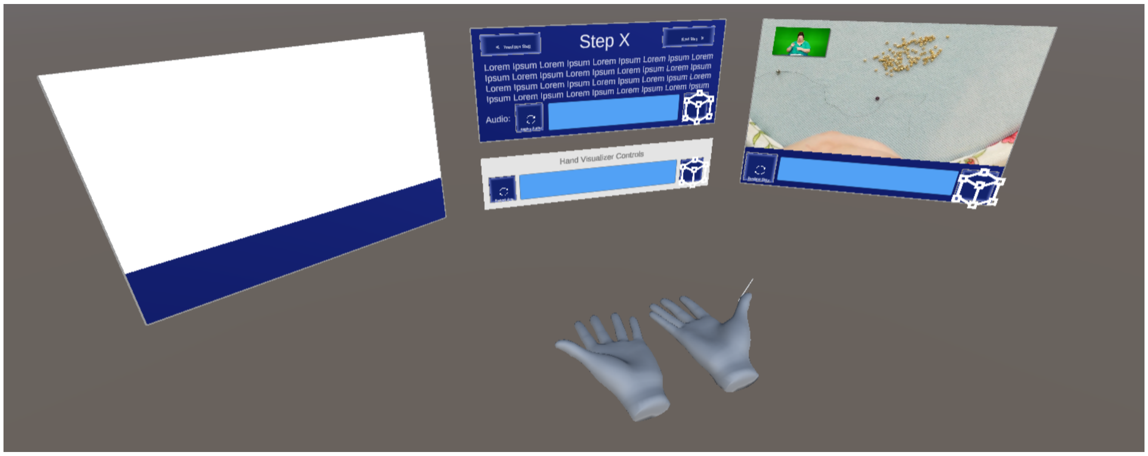


Figure 4.11: EmbodiAR: general scene layout

Step Panel

EmbodiAR teaches bead stitch patterns in a step-by-step process, controlled by the top middle panel. This step panel displays buttons for moving to the next step or previous step. Under the hood the step history is maintained by a stack, and the previous step button is disabled when the stack is empty (i.e., no more previous steps).

Additionally there is text rendered for the textual instruction for the current step. EmbodiAR plays an audio clip which reads the instructions, and the audio controls are located on the bottom of the step panel. Essentially, the user can either pause/play the audio, alongside the option to reset the clip to the beginning. In addition, there is a progress bar indicating the duration of the audio clip and the proportion of which has already played, which is based on current designs of progress bars.

Bead Representation

Depending on the learning settings, the system displays either the 2D figure or 3D bead model on the left-hand side of the step panel, or anchored to the user's left hand.

Beading Action

Depending on the learning settings, the system displays either the video or 3D virtual hands on the right-hand side of the step panel, or positioned in front of the user.

When the video is displayed, there are a set of controls similar to that of the audio controls. Essentially, it includes a pause/play toggle, option to reset video, and a progress bar. These controls are located directly under video.

When the 3D virtual hands are displayed, there is a new panel located under the step panel. This panel contains similar controls to the video controls. Essentially, it includes a pause/play toggle, option to reset the visualizer, and a progress bar. This panel also controls the progress of the dynamic elements of the 3D bead model as they are linked with the 3D virtual hands.

4.6.2 Learning Scene Settings Configuration

I designed this portion to be flexible so new learning scenes could be integrated to extend the capabilities of the system. I describe the structure of the configuration, which essentially contains the setting for the step instructions, 2D figure, 2D video, 3D bead model, and 3D virtual hands.

Step Instructions

To configure the step instructions, the configuration requires two primary lists. The first list is for the textual instructions (uses strings), and the second list is for the audio instructions (uses audio files). The length of the list determines how many steps are present in the stitch.

To handle the option to loop steps, another list is used which indicates what is the following step. Essentially, this list features a list of indices and when you press next step it will go to the step indicated from the current step. Usually the next step would be the next index, however, setting the value to an earlier index will essentially loop the instructions (e.g., to define that step 10 loops back to step 5, then the value at the index for step 10 is the index of step 5). One limitation with this form of loop is that there is no exit condition, however, for the scope of this study it is not required.

2D Figure Settings

To configure the 2D figures, the configuration requires one list of textures. The length of this list correlates to that of the step instructions, such that for each step there is a referenced texture (i.e., an image of the figure at that step).

2D Video Settings

To configure the 2D video, the configuration requires a path to the video alongside a list of paired timestamps. The path essentially features either a URL or local data path for which the video can be loaded from. A paired timestamp is two floats: a value for when the video should start and a value for when the video should end.

Then constructing a list of these pairs, I could define segments in the video that render the actions to complete that step.

3D Bead Model Settings

To configure the 3D bead model, the settings required a reference to a 3D model prefab. Within the 3D model prefab, it required fields to be filled out for the stitch model controller.

For the stitch model controller, it required the 3D bead model to be segmented within steps. Similar to the configuration of the figures, each step had to be defined in the 3D model and then I linked a list of steps which indicates which state should be visible. I would like to note there are ways of improving this structure to improve extendibility, however this was sufficient for my study.

Additionally, the stitch model controller requires two lists, one to indicate the stringing actions and another to indicate the weaving actions. These lists are similarly sized to match the number of steps within the stitch. For the stringing actions (i.e., where the beads slide into place), each index was its own list of the destinations of the beads (e.g., size of four with four transforms of the beads indicates that four beads will be placed at those destinations).

To specify the stringing and threading actions for both the 3D bead model and 3D virtual hands, another list is required for the model events per step. Each step has its own list of model events, which can be either a stringing event for an individual bead, or a threading event (i.e., the purple trail indicator). A model event requires a timestamp of when it triggers, and an optional field depending on the event type. For the stringing event, I could specify the particular bead type (e.g, red cylindrical bead, blue seed bead, etc.). For the threading event, I could specify the duration of the trail. Within the 3D bead model, each step required a starting and ending index from the thread line renderer, and the purple trail would render over that span of thread for the set duration.

3D Virtual Hand Settings

To configure the 3D virtual hands, the settings were very similar to that of the video configuration. Instead of the video file, the configuration required the JSON file of the recorded hand movements. Similarly to the video, it required a list of paired timestamps. The same process used to segment the video is used for the 3D virtual hands. For the stringing and threading actions, it uses the same process as defined for the 3D bead model.

4.7 User Interaction Techniques

Within the learning scene, there are three different options for the user to interact with the system: *touch*, *voice commands*, and *eye gaze*. In this design, it was important to leverage the different interaction techniques provided by headworn AR headsets to understand how participants behave when interacting with the system.

As the context of the work involves working with beads, it is not expected that users will primarily use touch while working on their task. This is based on the findings found from Heinemann and Möller [32], where they found participants in the knitting tutorial had to stop their task to use a mouse to interact with the tutorial video. It is expected that the user will prefer voice commands and gaze due to the hands-free interaction.

Touch

Touch is a popular way to interact with virtual interfaces on the HoloLens 2, as the primary system interaction is through touch. The user can use either index finger to push down on virtual buttons.

Voice Commands

The user can use an assortment of voice commands to interact with the system. When the user would say a voice command, a corresponding action would occur. All implemented voice commands and their actions are described in Table 4.2. A cheat sheet of the voice commands for the context of the study can be found in Appendix J.

Table 4.2: Voice commands offered by EmbodiAR

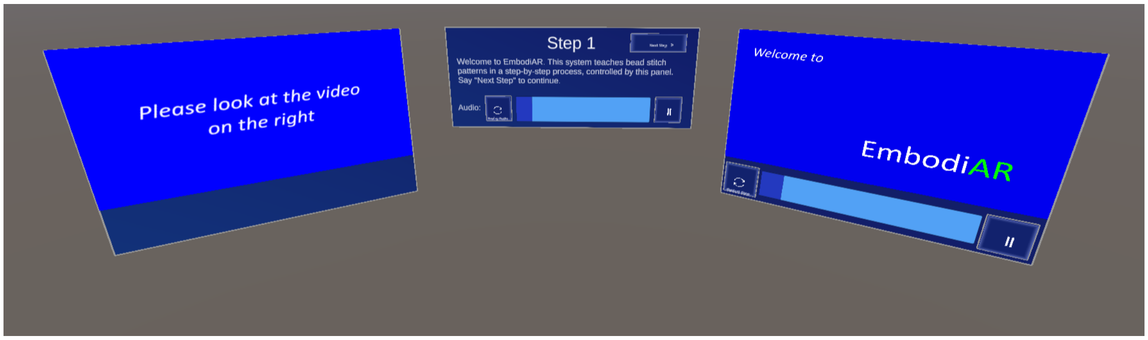
Keyword	**Action**	**Active Context**
”Next Step”	Iterates learning materials to the step after the current step	*Learning scene*
”Previous Step”	Reverts learning materials to the step before the current step (if there are no previous steps, this has no effect)	*Learning scene*
”Play”	Resumes all learning materials (video, audio, 3D virtual hands, 3D bead model)	*Learning scene*
”Pause”	Stops all learning materials in their current state (video, audio, 3D virtual hands, 3D bead model)	*Learning scene*
”Reset”	All learning materials reset to the current state (video,audio, 3D virtual hands, 3D bead model).	*Learning scene*
”Recalibrate”	All virtual objects re-orient themselves relative to the headset’s position and orientation.	*Learning + Title scene*
”Load first trial”	Loads the learning scene for a given stitch and learning material defined for the first trial (Instructed by researcher)	*Title scene*
”Load second trial”	Loads the learning scene for a given stitch and learning material defined for the second trial (Instructed by researcher)	*Title scene*
”Stop trial now”	Saves/stops all data logging and returns the user to the title menu once saved.	*Learning scene*
”Go to title menu”	Exits the learning scene and goes to the title menu.	*Learning scene (Tutorial only)*

Eye Gaze

The user can use their eyes to stare at buttons to select them. The dwell configuration is based on given MRTK values, which are designed to not be too short for accidental selection, but not too long to be unpractical. These values include a 0.5 second dwell intent delay, where the system does not recognize the UI element is being gazed at until the threshold is met. Then there is a 0.5 second start delay, where the button highlights it is being gazed at but does not start the dwell action until the threshold is met. Then it takes two seconds to complete the dwell action, where the button is slowly increasing in highlight and providing audio feedback that it is being selected. Once it meets the threshold, the button is selected. Additionally, there are two seconds of delay allowed, such that if the user looks away briefly they can resume looking at it and not restart from the beginning.

4.8 EmbodiAR Tutorial

When the user opens the EmbodiAR tutorial, they will be greeted with the learning scene based on the traditional materials as shown in Figure 4.12. Traditional materials were selected to not overwhelm the user for what may be their first headworn AR experience. The goal of the tutorial is to teach the user how to interact with the system and the basic definitions of bead weaving. The complete tutorial is documented in Appendix E, however, the process is the following:


Please look at the video on the right

Step 1

Welcome to EmbodiAR. This system teaches bead stitch patterns in a step-by-step process, controlled by this panel. Say "Next Step" to continue.

Figure 4.12: EmbodiAR: tutorial snippet

1. Welcome user and describe purpose of system. Teach user about the step-by-step system and how to proceed to next step (using voice commands).

2. Teach user how to interact: touch, gaze, voice command.

3. Indicate there are a few bead weaving definitions that are important to understand.

4. “String a bead”: add a bead to their needle.

5. “Thread through a bead”: stick their needle through a bead already on their string.

6. Allow them to get comfortable, provide a voice command to exit the tutorial. Indicate how steps repeat if they were to move forward.

4.9 EmbodiAR Learning

In the title menu, users can either select the netting or peyote stitch. When one of these options are selected, the learning settings for the respective bead weaving stitch is used. Depending on the learning material option selected (Embodied AR, Static AR, or Videos and Figures), that would impact which learning materials are populated in the scene.

4.9.1 Netting Stitch

The steps for the netting stitch are outlined in Table 4.3. There are 19 steps in total which create three rows in the netting stitch. Once it reaches the end of step 19, it loops back to the second row as subsequent rows are completed identically.

4.9.2 Peyote Stitch

The steps for the peyote stitch are outlined in Table 4.4. There are 13 steps in total which create three rows in the netting stitch. Once it reaches the end of step 13, it loops back to the second row as subsequent rows are completed identically.

Table 4.3: Netting stitch step descriptions

Netting Stitch	
Step Number	**Instructions**
1	For a basic netting design, choose two colors. A main color (A) and an accent color (B).
2	Begin your netted piece by stringing the following bead pattern (BAA)- eight times. This pattern will give you a three section wide piece.
3	Go back through the fourth B bead from the end. This will complete the turn and the start of the next row.
4	String two A, one B, and two A beads.
5	Skip one B bead and go back through the next B bead.
6	String two A, one B, and two A beads.
7	Skip one B bead and go back through the next B bead.
8	To turn around and begin the next row: String two A, one B, and two A, one B, and two A beads. (AA B AA B AA)
9	Go back through the fourth B bead from the end. This will complete the turn and the start of the next row.
10	String two A, one B, and two A beads.
11	Skip one B bead and go back through the next B bead.
12	String two A, one B, and two A beads.
13	Skip one B bead and go back through the next B bead.
14	To turn around and begin the next row: String two A, one B, and two A, one B, and two A beads. (AA B AA B AA)
15	Go back through the fourth B bead from the end. This will complete the turn and the start of the next row.
16	String two A, one B, and two A beads.
17	Skip one B bead and go back through the next B bead.
18	String two A, one B, and two A beads.
19	Skip one B bead and go back through the next B bead. Then repeat step 8-19 to continue the pattern.

Table 4.4: Peyote stitch step descriptions

Peyote Stitch	
Step Number	**Instructions**
1	Begin your piece by stringing four beads, the first row. This pattern will give you a four bead wide piece.
2	While holding the other beads, string one more bead. This bead will be for the start of the next row.
3	Then skip the last bead you strung on the first row of beads and thread your needle through the next bead, going back in the direction towards the stop bead. Pull the thread tight so that the bead you just added sits stacked on top of the bead below it.
4	String 1 bead.
5	Then skip a bead, and thread through the next bead. Be sure to stack each bead on top of the bead on the prior row.
6	String 1 bead.
7	Fill the gap on the end, then thread through the first bead that is jutting out from the previous row. This will complete the turn and the start of the next row.
8	String 1 bead.
9	Fill the gap in the middle, thread through the last bead jutting out from the previous row. This will complete the current row.
10	String 1 bead.
11	Fill the gap on the end, then thread through the first bead that is jutting out from the previous row. This will complete the turn and the start of the next row.
12	String 1 bead.
13	Fill the gap in the middle, thread through the last bead jutting out from the previous row. This will complete the current row. Then repeat step 6-13 to continue the pattern.

4.10 Limitations for Learning

It is important to note the scope of what can be learned within EmbodiAR. This scope was limited due to constraints with the learning activities within the context of a comparative study.

1. EmbodiAR features *novice beadwork patterns*, thus the scope of the application does not explore how the learning materials scale to more difficult styles of stitches.
2. EmbodiAR does not teach more than how to make the pattern (e.g., planning an accessory or clothing). The step-by-step process used does not indicate an end condition or overall goal.
3. EmbodiAR does not teach how to prepare the needle and thread. For the context of the study, the preparation steps are done ahead of time due to time limitations and thus were not included.
4. EmbodiAR does not teach how to extend the thread for additional length. For the context of the study, sufficient thread is given such that participants would not run out. Thus, the instructions for how to extend the thread were not included.

4.11 Summary

EmbodiAR is a headworn AR system that allows novice bead weavers to learn two stitches: 5-Bead netting (AKA netting) stitch and 1-Bead netting (AKA peyote) stitch. Users can either use a traditional form of learning materials (videos and figures), or another AR representation which utilizes hand gestures and a 3D bead model. The learning process is segmented into a step-by-step process and users can interact with the system using voice, touch, and/or gaze. The system provides an extendable way for incorporating more stitches and possibly expanding towards more use cases of handcraft. In the tutorial, users can first learn how to interact with the system and basic bead weaving terminology. Once they are ready, they can enter the learning scene to progress through the steps while they bead weave. Limitations of

EmbodiAR include: narrow scope of novice beadwork patterns, does not teach how to prepare the materials before beginning the stitch, and also does not teach how to extend the materials or how to create anything beyond the beadwork pattern (e.g., an accessory or piece of clothing).

Chapter 5

Evaluation

5.1 Introduction

I use EmbodiAR as an experimental apparatus in a comparative study of learning materials commonly used in bead weaving and the embodied AR representations implemented in the tool. Here I describe the design of the study in addition to the data analysis methods employed.

5.2 Study Design

5.2.1 Research Questions

For my research, I have two research questions:

1. How do visualized hands and a dynamic 3D bead model compare to traditional learning materials (videos and figures) for learning handcraft with bead weaving as a focus?
2. How do visualizing hands and a dynamic 3D bead model compare when positioned at the place of work vs fixed in space for learning handcraft with bead weaving as a focus?

These research questions help us to answer our broader research questions within the Gesture and Form project, which are:

1. What are the possibilities and limitations of AR to capture, encode, and represent gestures involved in the making of beaded objects and textile-based architectural components?
2. How might AR be used to communicate this knowledge to others and what are the implications for forms of collaboration, the division of labor, and mastery

or expertise in various occupational settings and with regard to the sharing and preserving of cultural heritage?

5.2.2 Study Design Overview

For this mixed within/between-subjects study, I recruited 30 participants to use EmbodiAR using two of out of three learning conditions. These learning conditions include: Videos and Figures, Static AR, and Embodied AR. The conditions are simulated in Figure 5.1, however in the study these are deployed in AR; the placement is simulated due to field of view constraints with the HoloLens 2 for reporting. Each participant would be briefed, trained, and complete two bead weaving trials. After each trial, the participant would complete a post-trial questionnaire relating to their experience. Following both trials was a post-experiment interview to derive feedback on aspects the participant may have liked or disliked. Following the interview, the participant filled out a post-session questionnaire regarding their background information and final learning material preferences.

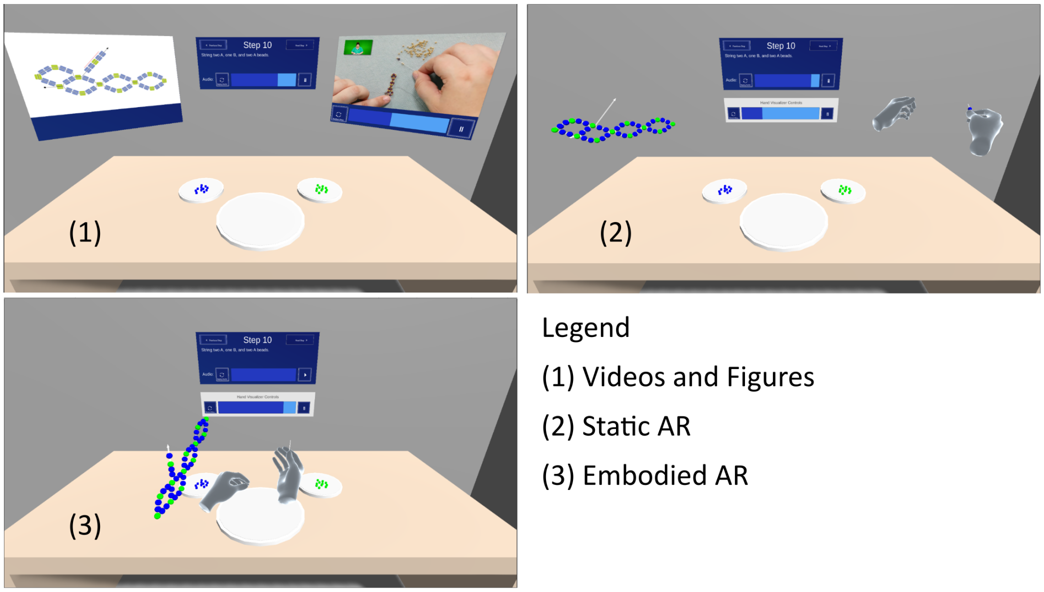


Figure 5.1: Simulated study conditions

5.2.3 Data Collection Instruments

HoloLens 2

I used a HoloLens 2 device to run EmbodiAR in addition to using its tracking capabilities for software logging. I recorded two categories of textual logging (events and sensor stream), and video recordings.

I added a function to EmbodiAR to assist in controlling the conditions for each participant when loading the respective trial. It uses a file called 'StudyConditions.txt' located in the application's persistent data path which contains the participant ID, first trial stitch, first trial learning material, second trial stitch, and second trial learning material. The system generates a verification code in the title menu UI, which can be referenced to ensure the conditions are setup properly. A full list of verification codes can be seen in Appendix I.

For the textual logging, all text gets saved to a local file on the EmbodiAR's application persistent data path. A new file gets created for each trial and auto-generates a filename based on the participant ID, condition, and timestamp (e.g., "LoggingInfo-2-Netting-20210928-134138.txt"). Upon starting the logging process, the first log entry also includes the participant ID and condition number in addition to the stitch for easier filtering for a batch data analysis. Each element within the log follows the base format of *[Tag][Timestamp] info;*.

The events in the textual logging include interaction events (e.g., button selected, gaze dwell event, voice command), and state changes (e.g., video paused/set playing/set stopped, etc.). These events are logged the moment they occur.

The sensor stream in the textual logging includes: head pose, eye tracking info, and hand tracking info. These differ from the events as these are logged at a fixed frequency of four Hertz. The frequency was derived experimentally as a balance between rich data to sufficiently recreate the actions while minimizing data overhead. The head pose captures the position and orientation the headset is facing. The eye tracking info captures the position and orientation of the eyes, in addition to which direction they are looking. The hand tracking info is similar to the hand recording app where it captures the position and orientation of all joints in each hand.

The video recording captured at a resolution of 896x504 at 30 frames per second.

It captured the holograms visible within the HoloLens, allowing the rendered region of the holograms to be captured. It was set to capture the audio of both the application and microphone to ensure the video recording captured the context of the work.

Post-Trial Questionnaire

I used a questionnaire after each trial to quantitatively capture the participant's experience. The post-trial questionnaire consisted of three sections: bead weaving experience with given learning material, the NASA-TLX [31], and the SUS [7]. The post-trial questionnaire can be found in Appendix F and was used in a paper format for convenience. .

Post-Session Questionnaire

I used a questionnaire after the interview to capture the participant's background information in combination with a review of the learning materials they encountered in both conditions. The post-session questionnaire can be found in Appendix H and was also used in a paper format for consistency between questionnaire delivery format.

5.2.4 Video Camera

A video camera and tripod were used to collect the video of the hands working with the beads. The video camera captured video at a resolution of 720x480 and at a frame rate of 29.97 frames per second. This captured the context of the hands as it worked with the beads, as the HoloLens video stream has a limited field of view and does not sufficiently film the hands. When positioned over the shoulder, it provided the most optimal recording frame, however, still had limitations if participant's cover the work with their hands.

The video camera was also used to capture the semi-structured interview which was conducted after both trials to gain insights on the participant's experience. This was as it could capture the audio of the conversation and video of the beadwork if the participant wanted to refer to an element of the beadwork. The full list of interview questions can be found in Appendix G.

5.2.5 Study Preparation

Materials

For this study, I required a large quantity of beads, thread, and tapestry needles. Each participant required eight grams of red cylinder beads (size eight, Delicas), 16 grams of matte blue Czech seedbeads (size six), and 16 grams of hunter green seedbeads (size six). A scale was used to portion each group of beads. A bulk order of beads was purchased via BeadFx[1], and each grouping of beads was partitioned into individual bags for each participant. This was beneficial for both COVID-19 protocols to avoid reusing beads, and maintaining a consistent number of resources between participants. Spare unused beads were stored separately and made available if participants ran out of beads.

To simplify the bead weaving process, the steps to prepare the tapestry needle and thread were completed ahead of the study. Although preparing the needle and thread themselves would be better for teaching bead weaving overall, reducing this step allowed for a greater focus on the learning material for learning bead weaving patterns. For preparation, I cut a length of thread (4.5 feet) and fed it through the eye of the needle. This length was sufficient for allowing a stitch to be created without needing to add new thread. Once threaded through, it was tied off five times to decrease the chance of the needle coming loose. Once the needle was secured, I threaded the needle through a bead which acts as a stopper bead (stops new beads from fall off the thread). I threaded the needle through the stopper bead five times to ensure the stopper bead was secure. As the stitches were two different colors, I prepared two different sets of needles featuring different colored stopper beads. The netting stitch (blue and green beads) had a red stopper bead, whereas the peyote stitch (red beads) had a green stopper bead. This action allowed the stopper bead to not be mistaken as a threaded bead during the bead weaving process.

To capture the questionnaire responses and consent, my research colleague printed and photocopied the post-trial and post-session questionnaires, and informed consent forms. In total we prepared 66 post-trial questionnaires (2 per participant, 6 extra as buffer), 33 post-session questionnaires (1 per participant, 3 extra as buffer), and

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[1] https://www.beadfx.com

33 informed consent forms (1 per participant, 3 extra as buffer).

Room Layout

For the study, the selected room layout matched that of Figure 5.2. As wearing a mask while using the HoloLens 2 could fog the display, participants required the option to remove their mask if it impeded their ability to use the system. To mitigate the COVID risks, we positioned the bead weaving station inside a ventilated standalone room which was separated from the primary room by a glass wall. Thus, I could still directly observe and communicate with the participant if any technical difficulties arose. This allowed the participant to optionally remove their mask while working on their task. The room ventilation was also supported by an additional high efficiency particulate air filter (HEPA filter) for increased air quality. We had a plan to supplement conversation utilizing connected laptops for a voice call, however the ability to communicate was sufficient without it.

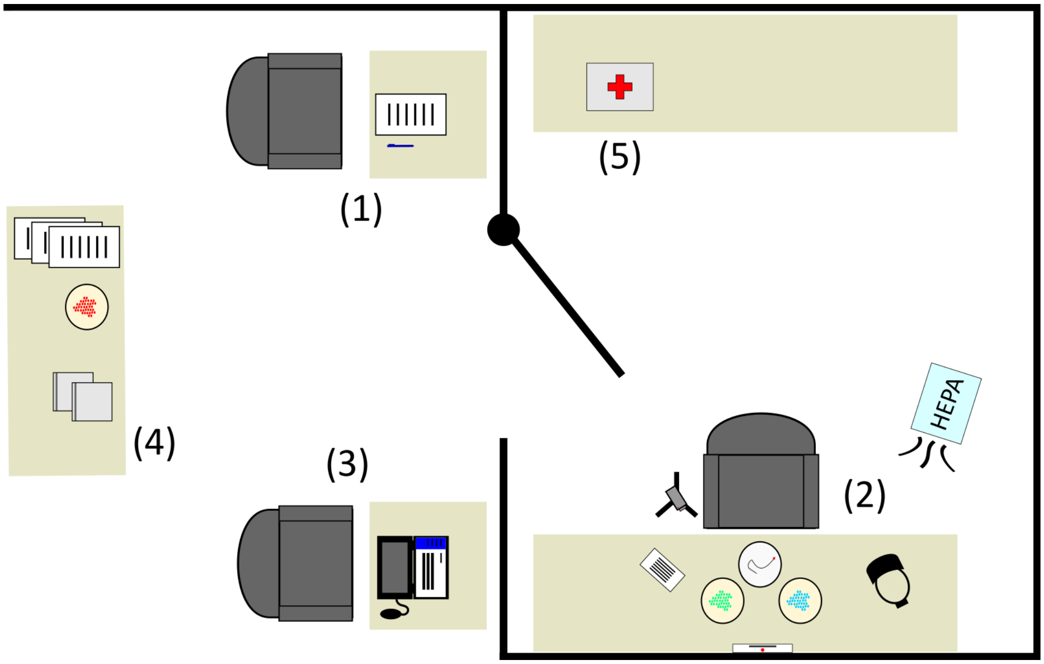


Figure 5.2: Room layout for study. (1) participant form station. (2) participant bead weaving station. (3) researcher station. (4) materials table. (5) medical supplies table.

While the bead weaving station was positioned inside the standalone room, the station where the participant filled out forms was positioned outside the room. Thus once the participant was no longer using the HoloLens 2, they would require their mask and fill out their forms. This allowed an opportunity to set up the bead weaving station for the necessary trials during the study. The materials were set up outside the room so most of the supplies could be prepared while the participant is at the bead weaving station, and thus minimizing the time required in the standalone room.

Participants were expected to use tapestry needles for bead weaving, so I supplied rubbing alcohol and bandages in case they pricked themselves with the needle. In the scenario thread got stuck on the participant's body, scissors were be on standby to cut the thread. These were positioned within the standalone room but out of the way so participants did not need to be concerned about what minimal dangers were present. Throughout the study none of these materials were required, however they were beneficial as a precaution.

Figure 5.3: Layout for bead weaving station.

The concrete layout of the bead weaving station is shown in Figure 5.3. A non-sliding chair is centered along the table to reduce the chances for participants to move around while completing the task. This was to assist in keeping the hands in frame of the camera which was positioned over the participant's shoulder. The frame of the video is shown in Figure 5.4, alongside the placement of the beading plates for both bead weaving stitches. A large white plate was positioned in front the participant which acted as their working space where they would complete the beadwork. One-to-two slightly smaller plates were positioned by the plate to the left and right which held the unused beads. Additionally, on the wall in front of the participant was an instruction on calibration which said "View not aligned properly? Look at the red circle and say: 'Recalibrate'" alongside a red circle which is centered on the wall at the eye level of a participant when seated. The HoloLens 2 charging station was located on the same table to quickly allow charging to start once the participants were finished to ensure it was fully charged for the next participant.

Figure 5.4: Video camera recording frame and bead placements per stitch: netting (left) and peyote (right)

5.2.6 Recruitment

Participant Criteria

I required 30 participants with the following criteria.

1. *13 years of age or older.* I wanted to exclude participants aged 12 and under according to the product safety warning and instructions for the HoloLens 2 [57].

2. *Have little to no experience bead weaving.* As the study measures the differences in beginner knowledge learned, previous knowledge could likely result in no additional learning.

3. *Have reasonable vision and head mobility.* As it could impact the ability to use and interact with the HoloLens 2.

4. *Be right-handed (or ambidextrous) to be comfortable bead weaving using your right hand.* The handedness in all the learning materials are designed from right handed bead weavers. This criteria was to avoid a potential confound on effectiveness of right handed material on left handed bead weavers.

5. *Have no hand/finger disabilities that will prevent you from bead weaving.* As disabilities such as hand fractures, severe arthritis, amputation, essential tremor, etc. could impact how participants would interact with the beads.

I also excluded members of the labs involved in the project and the greater Gesture and Form project to avoid a conflict of interest. There were no other selection criteria for our participants, however they were pulled from Halifax Regional Municipality university student populations due to our recruitment strategy.

Recruitment Protocol

I utilized a convenience sampling recruitment strategy. I sent a recruitment notice to the Dalhousie University Computer Science undergraduate and graduate mailing list. The recruitment notice outlined the study (process, eligibility criteria, data collection, compensation) and instructions to contact the main researcher. Once potential participants inquired interest, the main researcher emailed them a confidential doodle poll to fill out which time slots they were available. Session invites were done on a first-come first-serve basis on when availability was submitted. An alternative wait-list doodle poll was distributed to other potential participants once the initial slots were filled. The wait-list doodle poll matched all current session in addition to more sessions outside of the initial planned range. When participants either canceled or did not show up to sessions, potential participants from the wait-list were invited also on a first-come first-serve order; either replacing the same slot or extending into slots after the original scheduled times.

5.2.7 Study Procedure

Participant Arrival

Participants were instructed to arrive outside of the lab door five minutes before the scheduled start time. On weekends and holidays, the participants were instructed to arrive outside the building main doors due to the outer doors being locked. Once the participant arrived, they were greeted, asked to sanitize their hands, and directed into a chair inside the lab room (but outside the bead weaving room).

Briefing and Consent

I then welcomed and briefed the participant on the flow of the study, consent process, data collection process, and some instructions to keep in mind during the study. These include avoiding to excessively move to stay within the frame of the camera and system calibration. That I would avoid giving bead weaving related help but to let us know if there were any technical issues. The process of being able to restart and request a new thread, needle, and beads. Additionally, participants were instructed to try to look at each learning resource available as it is all trying to help, such that they can provide informed feedback. I motivated that their work should look like the pieces shown in the instructions as mistakes can easily snowball into more mistakes. Lastly, participants were asked if they have any questions. Once satisfied, the participants were directed to read and sign the informed consent form.

HoloLens 2 Setup and Calibration

After the consent form was signed, the participant was led into the bead weaving room. In the case the participant did not consent, they would have been led out (although this did not happen). Once in the bead weaving room I turned on and introduced the augmented reality headset (HoloLens 2) and the three ways to adjust it for their head. Participants were also taught how to change the volume and brightness if the system was too loud/quiet or too bright/dim. Some participants turned up the volume, and I did not observe any participants adjusting the brightness settings. Once the participant was briefed on how to wear the HoloLens 2, they were instructed to sit in the designated chair and put on the headset. After the participant adjusted the fit, they were asked if it was comfortable as it was important as they would be wearing it for a while. Once comfortable, they were instructed to calibrate the system for their eyes by pressing the “Adjust” button in the pop-up that appears once new users start wearing the HoloLens 2 (ensuring the full view and proper eye calibration). As the application calibrates upon device startup, I instructed the participants to re-calibrate the application by looking ahead at the red dot taped to the wall and say the keyword “re-calibrate”. Participants were instructed to re-calibrate if the view was misaligned.

Tutorial

Once calibrated, the participants were told next up would be the tutorial. I briefed the participants that I would be available if they had questions during the tutorial process and that I would bring up pointers as they progressed. In most cases, the participants did not have questions during the tutorial process. The participants were instructed to open the tutorial by pressing the “open” button on the top left of the application. Once the tutorial was loaded, I would stream the HoloLens 2 in low video quality from our laptop to preview their visuals. If the calibration was misaligned I would remind them to re-calibrate so they could see what proper calibration looked like during the bead weaving learning process. Based on audio cues from the system, I would give the participant additional pointers to supplement the tutorial process. These include pointing out the cheat sheet of voice commands on the table after being introduced to the interaction techniques. Additionally, once the participant was entering the bead weaving base definitions, they were reminded there will be a figure on the left and video on the right detailing the next two steps (the two definitions). After the threading tutorial step audio cue finished (while the video is playing), I instructed the importance of pulling the thread tight after threading through a bead to help maintain the structure of the beads. Once participants reached the end of the tutorial, once they were comfortable with the interactions and definitions, they were permitted to exit the tutorial via the voice command “Go to title menu”.

First Trial

Once back in the title menu, I briefed the participants that proper calibration is important for the trials. Next I provided an indication of what learning resources will appear and where (e.g., 3D bead model attached to the left hand and 3D hands in front of them). To begin the first trial, I told them to say the command *load first trial* while looking straight ahead for proper calibration until the content loads in where they are free to look around. Additionally, once the content loaded in they were permitted to begin bead weaving.

Once the trial loaded, I noted the time I would need to stop the trial (i.e., 35 minutes after it loaded). During these 35 minutes, the participant would bead weave without additional assistance. Once the time was a minute away from finishing, I instructed the participant to finish their current action and once tightened to say the voice command *stop trial now.* Once it returned to the menu (data completed saving) they were permitted to remove the HoloLens and then directed out of the room to fill out the first post-trial questionnaire.

As they filled out the questionnaire, I would collect the beading materials and set up the beading materials for the next trial. Used beads were stored in a bag marked *used*, and the beadwork was kept on the plate to the side. Once the participant finished the questionnaire, they were led back into the bead weaving room.

Second Trial

Once seated, the participants were instructed to put the HoloLens back on. If I noticed the power indicator was turned off, the participants were instructed and verbally guided how to turn the HoloLens on again. Once loaded in the title menu, the participant was reminded about the importance of calibration, and once ready could say the voice command *load second trial* to begin.

The second trial followed the same procedure as the first trial during the 35 minute duration and once completed directed out of the room to fill out the second post-trial questionnaire. As they filled out the questionnaire, I would similarly collect the used beading materials. However, the two completed pieces of beadwork would now be positioned in frame of the video camera. I would re-orient the participant chair towards the door where I would later pull their chair for the post-experiment interview. Once the participant was done the questionnaire, they would be directed back into the room.

Interview

Once seated, the participant would be briefed on the process of the interview. I indicate that I will be using the video camera to record the interview, and that it will remain trained on the beads so if they wanted to point anything that can be recorded, otherwise it is primarily recording the audio. This is to ensure they are aware I was not video recording their faces, allowing them to be more comfortable for the interviewing process. I prompt the participant if they are ready, and when confirmed will start the interview recording.

I start with the first question and ask each question in order unless the participant strongly tends toward a different question during their explanation. Priority was in keeping the conversation fluid, while following of the order the questions was second. If interesting points occurred, I would prompt for additional explanation, otherwise asked primarily the listed questions.

Once the interview was nearing completion, if the participant had no other feedback to add then I stopped the video recording. Once stopped, I directed the participant out of the room to fill out the post-session questionnaire.

Closing

Once the participant completed the post-session questionnaire, they were compensated and thanked for their participation in the study. I then led the participant outside of the lab.

Preparation for Next Participant

After the session has concluded, it was important to sanitize the equipment, offload the data, put away the completed beadwork and prepare for the next participant.

I used alcohol sanitizing wipes to clean all the equipment (HoloLens 2, pen, plates) alongside a disinfectant spray to clean all work surfaces (table tops, chair contact surfaces).

I downloaded the recorded video and logging data from the HoloLens 2 via the device portal. Concurrently I transferred the video files from the video camera via a direct USB cable connection. Once the files were downloaded/transferred and verified (i.e., opened up the file to ensure it was not corrupt) the original data file on the instrument was deleted. These files were then uploaded the Gesture and Form's SharePoint [58] file repository.

While the files were being handled, I also took pictures of the beadwork produced by the participant. Then I individually bagged each of the beadwork and stored it. Following I prepared the beads and forms for the next participant. I set up the bead weaving station with the material for the first trial, and the consent form at the form station.

Counterbalancing

To mitigate ordering effects I followed numerous steps for counterbalancing. From the pool of 30 participants, each had to do two of the three conditions. So I had 3 sections of 10 participants each doing (condition 1+2, 1+3, 2+3), having 20 participants complete each condition.

Each section was counterbalanced where half of the participants would do one condition first, and the other half would do that condition second. This reduced the ordering effect between conditions.

I counterbalanced for the ordering of the stitch, where half of the participants completed the netting stitch first and the other half completed the peyote stitch first.

The order in which the participants completed the sessions was counterbalanced to reduce an effect from the study as it proceeds. The end result of the counterbalancing can seen in Appendix I.

5.3 Data Analysis Structure

From the data collected within the study, I will now cover the data analysis process used.

I answer the research questions using essentially three primary components: how did the participants feel, what did the participants do, and what did they create. The interview transcripts were analyzed qualitatively to identify how participants feel about the different learning materials and to derive some potentially meaningful insights. This is supplemented by a quantitative analysis of the questionnaire responses to test for significant differences for the responses between the conditions. I performed an analysis on the sequence diagram generated from the actions during the trials to understand how they interacted with the learning materials. Lastly, I performed an analysis on the resulting beadwork from the study to find if different learning approaches result in varying quality of beadwork.

5.3.1 Post-Trial and Post-Experiment Questionnaires

The participant data within the post-experiment questionnaire was summarized to report a representation of my study sample population.

My research colleague assisted with a portion of the quantitative data analysis for the scope of executing some statistical tests. For the post-trial questionnaires which contained the bead weaving experience questions and the SUS and NASA-TLX standardized questionnaires, we used the Shapiro-Wilk normality test [70] to find if the responses followed a normal distribution. For distributions we could assume normality, we used ANOVA to reveal any significant differences to evaluate differences across the three conditions. For distributions we could not assume normality, we used the Kruskal-Wallis Test [45] to similarly reveal any significant differences to evaluate differences across the three conditions. I followed a similar process for the learning material helpfulness from the post-session questionnaire.

5.3.2 Logging Data and Video

I generated a set of timestamped actions from the logging data with observations from the video data. The interaction data was derived from the logging data and used the videos to inform the blanks.

The gaze data was used to determine the gaze targets for each participant. The workspace was divided into four quadrants as pictured in Figure 5.5. There are five gaze target categories where the red area is the *Area of Work*, blue area is *Model*, green area is *Video/Hands*, white area is *Step Instructions*, and any other area is categorized as *Out of Bounds*. This setup accurately describes the gaze data of the Static AR and Video and Figures, however it is slightly misleading for Embodied AR.

As the 3D bead model and 3D virtual hands are placed within the area of work, the gaze data is not accurate to discern what is being focused on if there are overlapping elements. For the gaze data, all sessions were normalized into 180 buckets (e.g., 30 minute session would segment into 10 seconds). To determine the focus, the category which had the greatest mean focus time during the respective bucket interval was represented as the focus target. Due to the bucket size, behaviors such as quick glances are lost, however more general behaviors would be lost with more complex sequence diagrams.

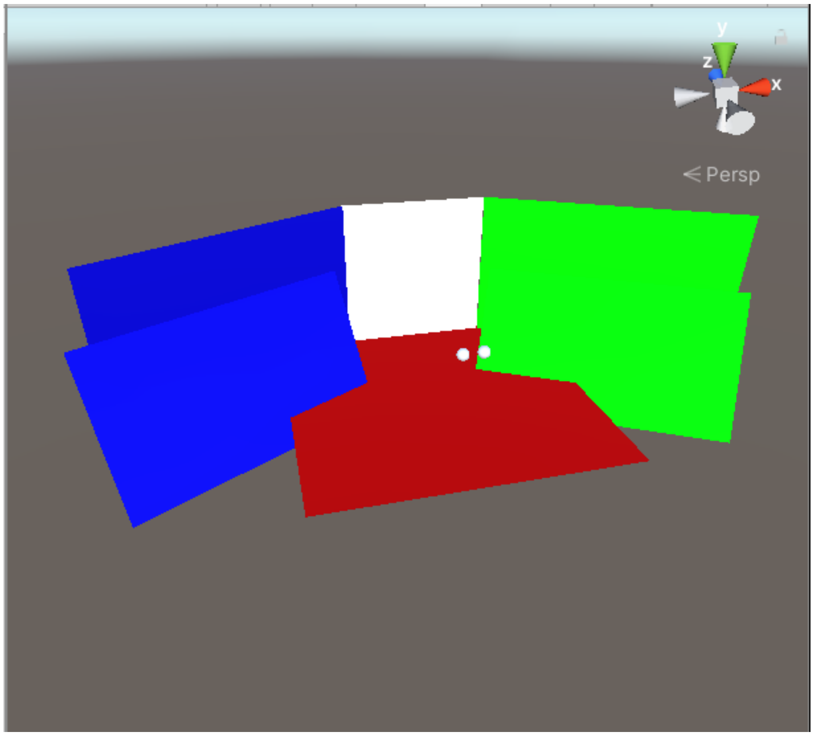


Figure 5.5: Eye gaze target quadrants for detecting where participants were looking

Using this set of gaze data, another research colleague assisted me in using the TraMineR package [24] in R [64] to provide visual representations of action patterns for individual tests and across all approaches we assessed. From this, we were able to derive a set of behaviours while participants were interacting with the learning materials. We used a Z test on findings of interest to see if behaviours were different between certain proportions.

Additionally, using the remaining interaction data I analyzed how participants interacted with the system (i.e., counted number of voice commands, gaze to select, or touch between trials). I tallied how often people used voice, touch and gaze commands. Additionally, I explored if there were any patterns between where participants are looking and how they interact. As participants have to look at the button for gaze and touch, I assume they would be looking at their target. However for voice commands no target is required, so I investigate where they are looking when they interact with voice commands. To determine this, I constructed a frequency table with the combination of where the participants are looking and what voice command they used for each condition.

5.3.3 Beadwork

The quality of the resulting beadwork were evaluated through experts in bead weaving. The beadwork was characterized and rated to identify common issues or differences between the resulting beadwork. This helps answer the question if different approaches result in varying quality of beadwork.

To rate the beadwork, I devised a 5-point ranking scale which mimics modern 5-point rating systems. The scale uses the following descriptions:

1. No indication of proper stitch.
2. Few elements visible of proper stitch, mostly a mess.
3. Some elements visible of proper stitch, however has notable errors.
4. Mostly elements visible of proper stitch, few errors.
5. Correct indication of proper stitch, no errors.

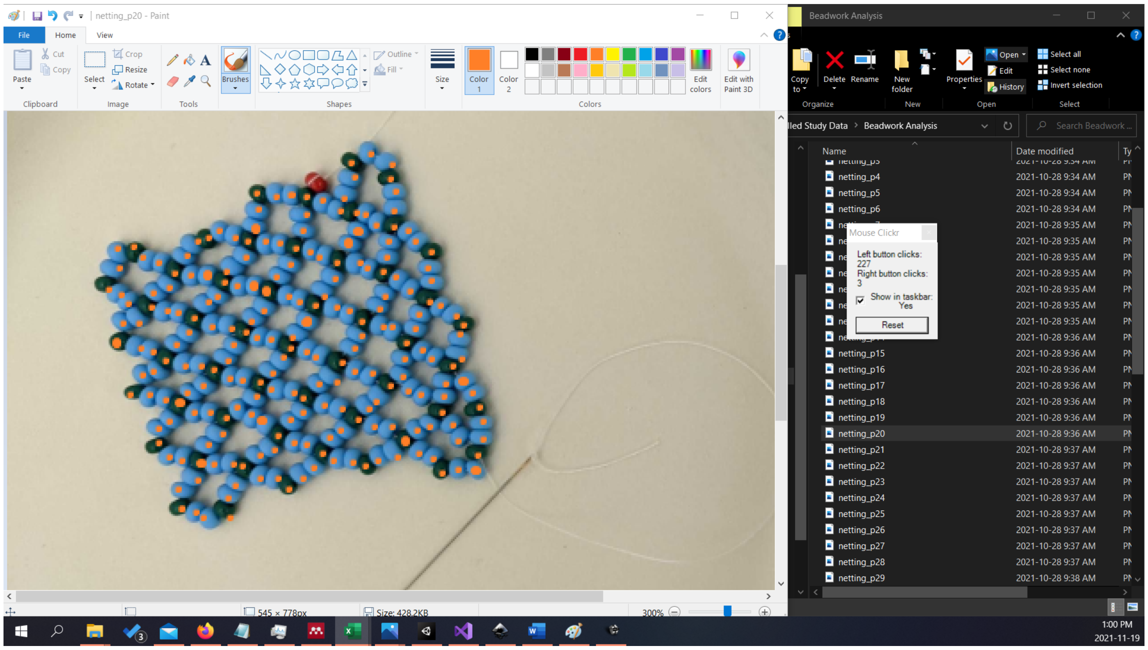
As participants may have been interrupted while stitching in their trial, the final bead may have been off in this case. Thus the ranking was stipulated to not penalize the work if the problem is with the very last bead.

Before the beadwork can be ranked, I first needed to prepare references images for each beadwork. I cropped the images, added the participant IDs on each piece, and exported the resulting images using Inkscape [13]. I then created two ranking templates (one for each stitch type) on Miro [60], which is an online collaborative whiteboarding tool. Then I uploaded the images to each respective template (30 images each). For easy ranking, there are 5 frames which correspond to each point in the scale. Thus, the process to rank each beadwork is simply dragging the image of the beadwork into the respective frame, allowing each beadwork to be seen next to similarly ranked beadwork.

To rank the beadwork I recruited two expert craftspeople who could provide additional insight on the beadwork produced. The qualifications we anticipated suitable for this insight was having experience teaching beadwork or related handcraft for at least 1 year. Two collaborators on the broader Gesture and Form project who had no prior affiliation with my study met these requirements and were able to assist in the ranking process.

The ranking process follows two phases. First, each ranker independently ranked the two sets of beadwork. To achieve this, each ranker had a private Miro page that was duplicated from the template. They were advised to not collaborate so we could reflect on the ranking scale and elicit reasons for why items may have been ranked differently. Once the beadwork was ranked, I compared and highlighted which ones were different. Then for the second phase we held a meeting where we covered the differences in ranking and tried to identify if there are any common issues or differences between the resulting beadwork. The meeting was recorded and the resulting themes were extracted from the meeting. With the ranked beadwork, we used two-way ANOVA to determine if there was a significant difference between the learning conditions and stitch type with regards to the beadwork ranking.

Following, I also conducted an analysis on the measure of work done for each stitch. I used the number of beads on the beadwork as a measure of how much work was done. I verified the distribution of mistakes between the stitches via a first pass inspection of the beadwork to ensure bead count could be a viable measure. I used the completed beadwork pictures to count the beads from which all beads were visible, and had the help from my research colleague to count the beadwork where the beads were not all visible in person. The latter happened for only 10/60 pieces of beadwork and generally was due to mistakes which made the beadwork turn into a mass of beads. To count the beadwork via the pictures, I used Microsoft Paint annotate the beads, and used the quantity of left clicks to determine how many beads were present as shown in Figure 5.6.



Left button clicks: 227
Right button clicks: 3
☑ Show in taskbar: Yes

Figure 5.6: Beadwork bead counting process using number of clicks

Once the beads were counted, I used the Shapiro-Wilk normality test to determine which beadwork followed a normal distribution. For distributions I could assume normality, I used ANOVA to reveal any statistically significant differences between the learning conditions and the measure of work done. For distributions I could not assume normality, I used the Kruskal-Wallis Test.

5.3.4 Interviews

To analyze the interviews, I first had to create transcripts of the interview audio. I extracted the audio into .WAV files from the interview video files using Vegas Pro 14 [26]. Then from the audio, I auto-generated transcripts using Microsoft Azure Cognitive Speech Services: speech-to-text [69]. Then I manually edited the transcript to add speaker labels (e.g., "R: " for Researcher or "P: " for Participant). Then I fix misinterpreted words using Microsoft Word [56] to create a verbatim transcript.

After reviewing the data, I constructed three categories of codes for the first round of organizing the data. The first category are codes based on the interview questions, the second are interesting codes for comparison of design elements, and lastly emergent categories which may not have been encapsulated within the other categories. This uses the element of structuring the data into categories from structural coding

Table 5.1: Category form for interview analysis

Participant ID	**Raw Transcript Data**	**Summary and Themes**
1	*lorem ipsum*	*lorem ipsum*
2	*lorem ipsum*	*lorem ipsum*
...	...	...
30	*lorem ipsum*	*lorem ipsum*

[68], however followed a different approach to generating the set of codes. While the codes may not directly tie each category specifically to a research question, the categories allow for comparisons between the conditions to capture similarities and differences while ensuring relevant information within the data corpus is not lost.

Then I parsed each transcript and tagged relevant segments of raw text for each category. As there is overlap between codes, there was overlap on the text which was coded for one-or-more categories. Due to this coding strategy, most of the transcript corpus was coded and not lost.

I constructed a form for each category as formatted in Table 5.1. The coded raw text for each category was then extracted into a form which had a row for each participant. This organized the data for further analysis.

For the second round, I iterated through each category form, and summarized and derived reoccurring aspects from each category. In addition, I calculated the proportions of overlapping themes across the participants to gain an understanding on the quantity of participants behind the theme. This ultimately resulted in a set of results on how participants felt about differences in the learning materials and the use of different aspects of EmbodiAR.

5.4 Summary

This chapter presented a mixed within-between subjects study design to compare the different learning conditions offered via EmbodiAR. Then, the data analysis plan for the data generated from the described study.

Chapter 6

Results

6.1 Introduction

Given the data generated from the study, I followed the data analysis plan described in the previous section to generate these results. I first describe the post-trial and post-session results using quantitative data analysis. Then I present an analysis on the behaviors derived from the participant's actions while they were bead weaving throughout the trials. Following are the results of the beadwork analysis, which describe the quality of the beadwork and measure of work done from each learning condition for each stitch. Lastly, is the interview analysis results which describes the results from each question and general reoccurring aspects found throughout the interviews.

6.2 Quantitative Questionnaire Results

6.2.1 Sample Population Demographics

Gender and Age

The sample population of 30 participants had a distribution of 43.33% female (13/30), 53.33% male (16/30), and 3.34% preferred not to say (1/30). Given I was not controlling the gender within the recruitment strategy, I reached a relatively balanced gender distribution.

All participants were in the age range of 18-29 years old, where half were within the range 18-22 (15/30), and the other half were within the range 23-29 (15/30).

Education

Given the question of what is the highest degree or level of education they have completed, the responses are illustrated in Figure 6.1. As the recruitment strategy targeted university students, there were a mixture of undergraduate and graduate level university students. Since the question targeted the highest degree completed of current students on the mailing lists, it can be derived that 43.33% (13/30) are undergraduate students, and 56.67% (17/30) are graduate students.

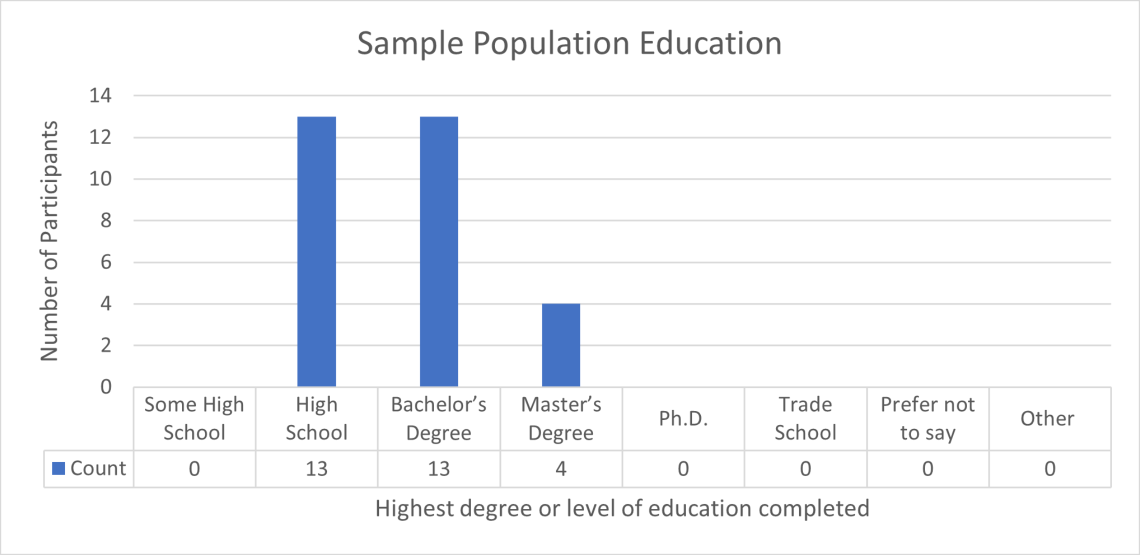


Figure 6.1: Education level of the sample population

Prior Experience with AR/VR

Given the question of where participants indicated how often the used AR and VR before this study, the distribution of the results are illustrated in Figure 6.2.

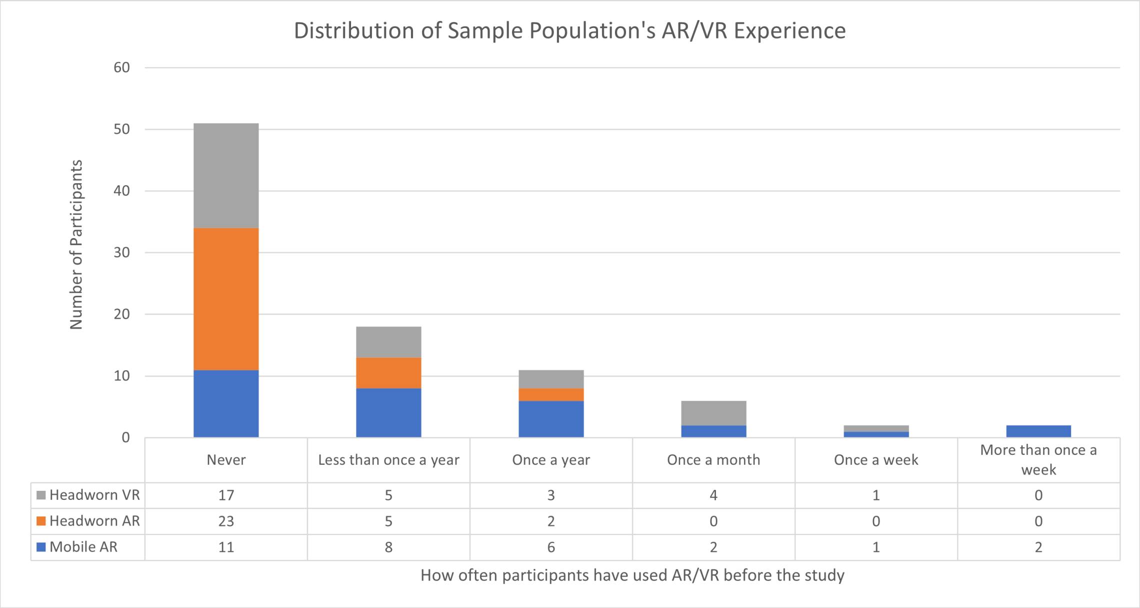
On a scale of 1-6:

- The average response for headworn AR is mean (M) 1.3 (tending towards *never*) with a standard deviation (SD) of 0.60.
- The average response for headworn VR is (M = 1.9, SD = 1.24): tending towards *less than once a year*.
- The average response for mobile AR is (M = 2.3, SD = 1.47): tending towards *less than once a year*.

The mode for each headworn AR, headworn VR, and mobile AR is ”Never”, indicating the participant had no experience.

Participants tended to have the least experience with headworn AR in comparison to headworn VR and mobile AR. This can likely be explained due to the higher barriers to entry for headworn AR in comparison to headworn VR and mobile AR. Most of our participants have some familiarity with either mobile AR or headworn VR, which could imply some familiarity with the style of virtual content provided in this study but being on a new medium of headworn AR.

In particular, 76.67% (23/30) have never used headworn AR, 16.67% (5/30) have used headworn AR less than once a year, and 6.67% (2/30) have used it once a year. This implies our sample population are mostly novices to headworn AR in addition to being novices to bead weaving.



	Never	Less than once a year	Once a year	Once a month	Once a week	More than once a week
▨ Headworn VR	17	5	3	4	1	0
🟧 Headworn AR	23	5	2	0	0	0
🟦 Mobile AR	11	8	6	2	1	2

Figure 6.2: Responses to the sample population's previous AR/VR experiences

6.2.2 SUS Results

The system usability scores of the different learning materials are shown in Figure 6.3. The score of the embodied AR learning condition received a 67.38, which is narrowly under the average SUS score of 68 [7]. However, the Static AR learning condition received a 71.38 and Videos and Figures received a 77.13 which are both good ratings.

The normality of the SUS scores was assessed. The Shapiro-Wilk test indicated that the scores were not normally distributed, $W(60) = 0.93, p = 0.003$.

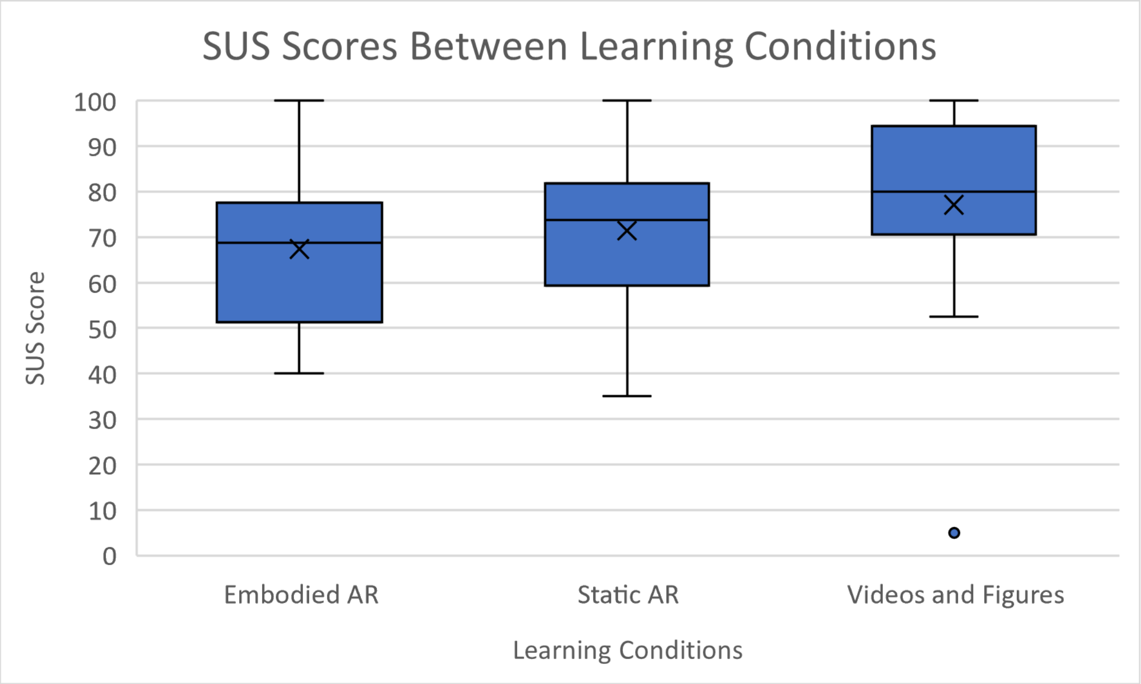


Figure 6.3: SUS rating between conditions

To evaluate the difference across three learning materials for bead weaving, we used the Kruskal-Wallis test ($\alpha = 0.05$). No significant differences ($\chi^2 = 4.79, p = 0.09, df = 2$) were found among the SUS scores across the three learning materials. While the scores of videos and figures are higher, the differences were not statistically significant.

6.2.3 NASA-TLX Results

The responses for the NASA-TLX questionnaire are reported in Figure 6.4. Using the Shapiro-Wilk normality test ($\alpha = 0.05$), we found which questions we can assume a normal distribution in Table 6.1.

Parametric Test

We used one-way ANOVA to evaluate the differences across the three learning materials for bead weaving on NASA-TLX ratings which followed a normal distribution.

No statistically significant differences were found between the learning conditions and: mental demand (F(2,57)=0.19, p=0.83), and effort (F(2,57)=0.25, p=0.78).

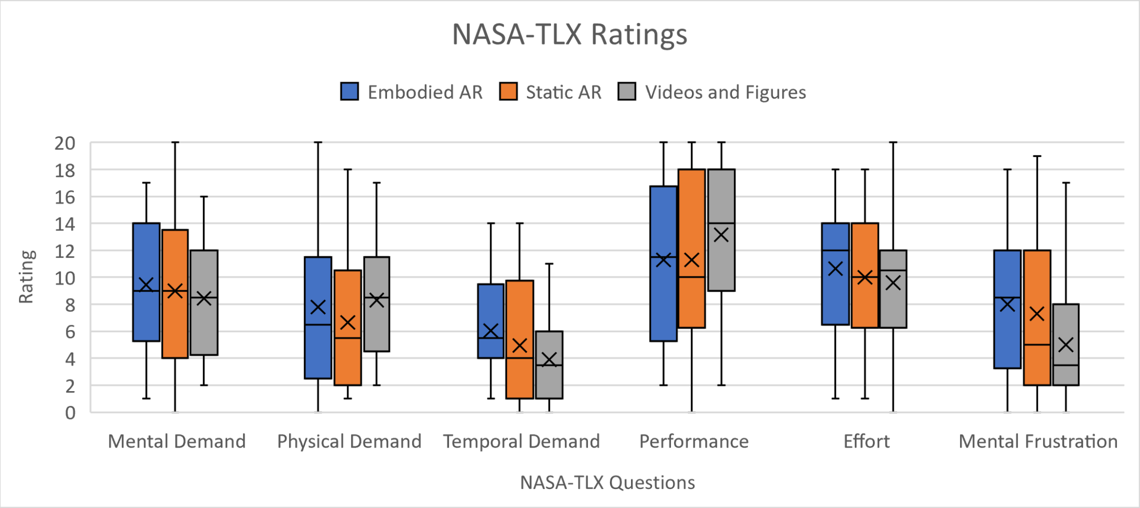


Figure 6.4: NASA-TLX ratings

Table 6.1: Normality of NASA-TLX ratings

NASA-TLX	**Shapiro-Wilk Normality Test** ($\alpha = 0.05$)		
	Test Statistic (W)	**p-value**	**Conclusion**
Mental Demand	0.97	0.11	Parametric
Physical Demand	0.95	0.02	Non-parametric
Temporal Demand	0.91	0.00	Non-parametric
Performance	0.91	0.00	Non-parametric
Effort	0.98	0.27	Parametric
Mental Frustration	0.91	0.00	Non-parametric

Non-parametric Test

We used the Kruskal-Wallis test to evaluate the differences across the three learning materials for bead weaving on NASA-TLX ratings which did not follow a normal distribution.

No statistically significant differences were found between the learning conditions on: physical demand ($\chi^2 = 1.49, p = 0.47, df = 2$), temporal demand ($\chi^2 = 3.18, p = 0.20, df = 2$), performance ($\chi^2 = 0.93, p = 0.63, df = 2$), and mental frustration ($\chi^2 = 3.03, p = 0.21, df = 2$).

Table 6.2: Bead weaving experience questionnaire questions

Question Tag	**Post-Trial Questionnaire Question**
Interest	*I am interested in learning bead weaving.*
Continuity	*I would continue learning bead weaving using this learning material.*
Learnability	*I learned new skills for bead weaving using this learning material.*
Ease	*The learning material was easy to follow*

6.2.4 Bead Weaving Experience Results

The responses gathered relating to the participant's interest in bead weaving and their experience with the learning material while bead weaving are shown in Figure 6.5. The shorthand tags in the figure reference the given post-trial questionnaire questions shown in Table 6.2.

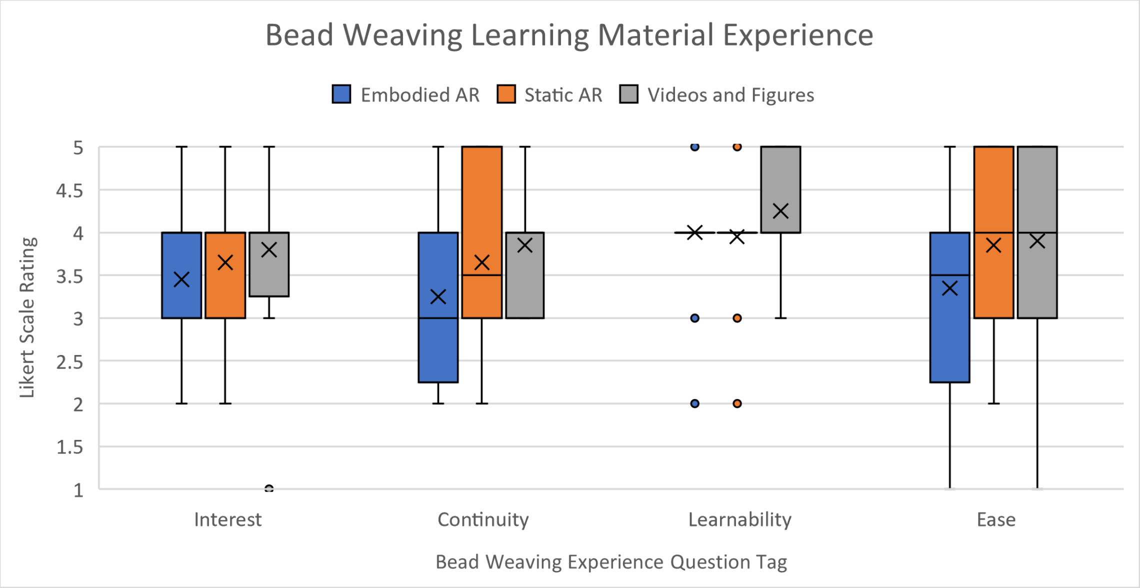


Figure 6.5: Bead weaving experience using learning material from post-trial questionnaire

The interest in bead weaving after completing a stitch utilizing the learning material is similarly distributed. The average interest level across all post-trial questionnaires in total was 3.63 (n=60) which ranges between *Neutral* and *Agree*. Across each learning condition the average interest level had (M = 3.45, SD = 0.83) after Embodied AR, (M = 3.65, SD = 0.93) after Static AR, and (M = 3.80, SD = 0.89) after Videos and Figures. The mode for the interest level after each learning condition was 4.

When prompted if participants would continue learning bead weaving with the given learning material, the AR learning conditions ranked slightly lower on average than for Videos and Figures. However, each learning conditioned ranked in between *Neutral* and *Agree*. Across each learning condition the average continuity level was (M = 3.25, SD = 1.02) for Embodied AR, (M = 3.68, SD = 1.09) for Static AR, and (M = 3.85, SD = 0.75) for Videos and Figures. The mode was 3 for Embodied AR and Static AR, and 4 for Videos and Figures. The desire to continue with the given learning material could be impacted by their interest in bead weaving above.

The learnability for each learning condition reached a rather high average rating. The learnability for Videos and Figures ranked slightly higher than that of the AR conditions. The AR conditions were distributed very similarly. Across each learning condition the average learnability was (M = 4, SD = 0.73) for Embodied AR, (M = 3.95, SD = 0.83) for Static AR, and (M = 4.25, SD = 0.64) for Videos and Figures which is closest to *Agree*. Each learning condition had a mode of 4.

The ease of being able to follow the learning material were ranked slightly higher for Static AR and Video and Figures in comparison to Embodied AR. Across each learning condition the average ease level was (M = 3.35, SD = 1.14) for Embodied AR, (M = 3.85, SD = 1.18) for Static AR, and (M = 3.90, SD = 1.02) for Videos and Figures. Embodied AR and Videos and Figures have a mode of 4, and Static AR has a mode of 5.

6.2.5 Learning Material Helpfulness Results

The responses gathered to the helpfulness of the different learning materials from the post-session questionnaire are first illustrated in pairs in Figure 6.6.

The normality of the learning material helpfulness scores were assessed. The Shapiro-Wilk test indicated that the scores were not normally distributed, $W(174) = 0.86, p < 0.001$.

To evaluate the difference across the learning material helpfulness scores, I used the Kruskal-Wallis test ($\alpha = 0.05$). Significant differences ($\chi^2 = 44.98, p < 0.01, df = 7$) were found among the learning materials. I used the Kruskal-Wallis test between every pair to determine which pairs of groups had significant differences, the raw results are found in Appendix M.1 and findings are described as follows. The differences

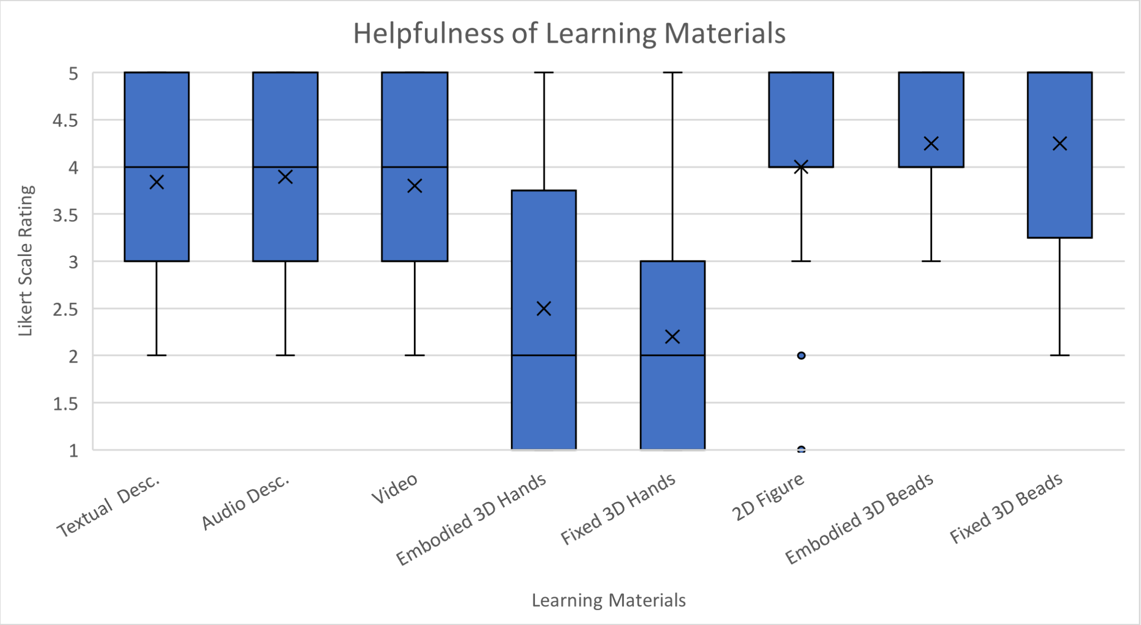


Figure 6.6: Learning material helpfulness

between the embodied 3D virtual hands and the fixed 3D virtual hands were found to be statistically significant. This indicates that the hand visualization was significantly less helpful than the other learning materials. No other statistically significant differences were found.

In addition, I break down the learning material helpfulness between the condition pairs as illustrated in Figure 6.7. Due to participants being exposed to two out of three conditions, the scores are separated into which pairs of conditions they experienced.

For the textual and audio description, the distribution between the conditions were very similar, however the helpfulness of the audio description seemed to tend higher than the textual description. For the difference in rating distribution for the fixed 3D hands tends to be more positive when experienced with Videos and Figures opposed to being experienced with Embodied AR, which could imply that a poor experience with the hands from the Embodied AR condition may negatively impact how they felt about the 3D hands in Static AR. Additionally, within the condition pair of Static AR & Videos and Figures, the fixed 3D hands distribution appears similar to that of the 2D video. Another potential explanation is that scores were ranked relatively to the most helpful and least helpful learning material available. Such that when the Embodied 3D Beads are experienced as most helpful, it potentially lowered

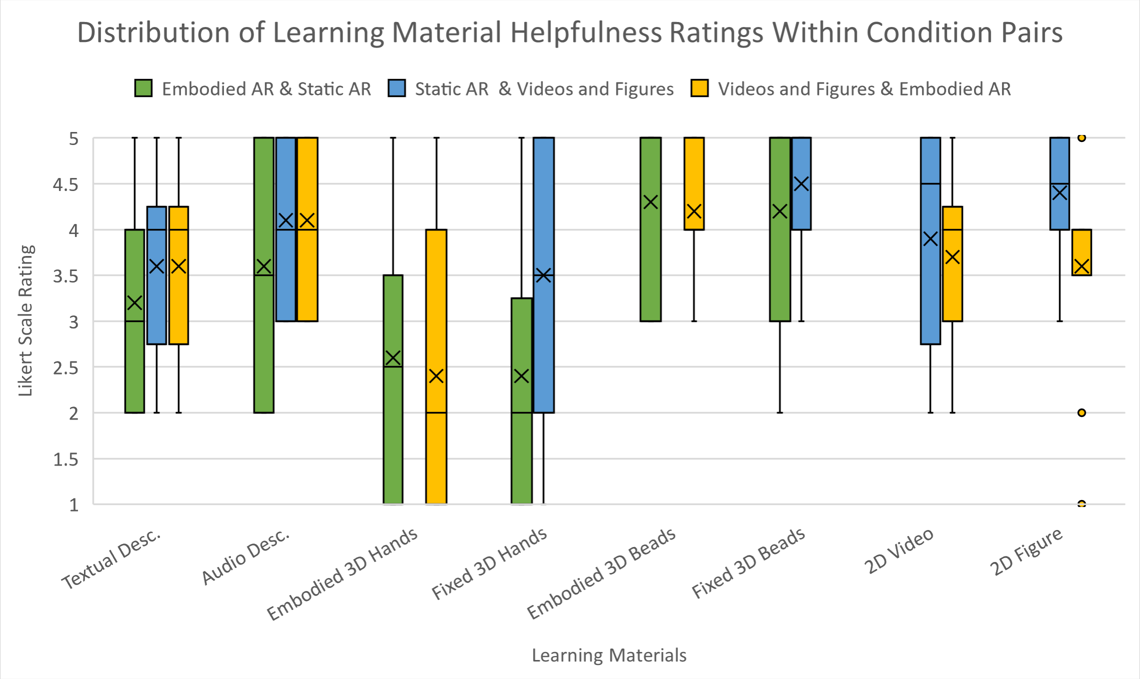


Figure 6.7: Learning material helpfulness split between condition pairs

the scores of other learning materials which were not as helpful in comparison.

The normality for each learning material pair is tested using the Shapiro-Wilk test, the results are shown in Table 6.3. As we could not assume normality across any distributions, I use the Kruskal-Wallis test to check for statistically significant differences; the results are shown in Table 6.4. No statistically significant differences were found between the learning conditions and helpfulness of the individual learning materials.

6.3 Behavioral Analysis

6.3.1 Focus of Attention

To evaluate the focus of attention, we generated sequence diagrams outlining where participants were focusing their attention as illustrated in Figure 6.8. However, it is important to note how for the Embodied AR the data representation could be misleading due to the location of the focus quadrants. As all learning materials are co-located at the area of work, the sequence diagram is not as analyzed due to potential of overlapping visible areas that the sequence diagram would be unrepresentative of

Table 6.3: Learning material helpfulness normality

Learning Material	**Shapiro-Wilk Normality Test** (Alpha = 0.05)		
	Test Statistic (W)	**p-value**	**Conclusion**
Textual Desc.	.86	0.00	Can't assume normality
Audio Desc.	0.83	0.00	Can't assume normality
Embodied 3D Hands	0.85	0.01	Can't assume normality
Fixed 3D Hands	0.87	0.01	Can't assume normality
Embodied 3D Beads	0.78	0.00	Can't assume normality
Fixed 3D Beads	0.73	0.00	Can't assume normality
2D Video	0.85	0.01	Can't assume normality
2D Figure	0.75	0.00	Can't assume normality

Table 6.4: Learning material helpfulness Kruskal-Wallis

Learning Material	**Kruskal-Wallis Rank-Sum Test** (Alpha = 0.05)			
	Chi squared	**df**	**p-value**	**Conclusion**
Textual Desc.	1.02	2	0.60	No significant differences
Audio Desc.	0.94	2	0.62	No significant differences
Embodied 3D Hands	0.12	1	0.73	No significant differences
Fixed 3D Hands	2.64	1	0.10	No significant differences
Embodied 3D Beads	0.28	1	0.60	No significant differences
Fixed 3D Beads	0.15	1	0.70	No significant differences
2D Video	0.30	1	0.58	No significant differences
2D Figure	3.27	1	0.07	No significant differences

their focus. This representation is still useful to see the relationship between the focus at the area of work (with the learning materials) as opposed to other areas such as the steps and out of bounds.


Embodied AR

Static AR

Videos and Figures

Figure 6.8: Participant area of eye focus throughout trials

The raw sequence diagram illustrated in Figure 6.8 show complex transitions between the areas of focus. Thus, we generated more representations to aid in the analysis of the sequence diagram. Due to the complex sequence representations, there were little-to-no instances where two participants looked at the same areas at the same time within conditions. This can be verified with the weighted frequency sequence diagram which appears the same as the unweighted frequency diagrams, which can be found in Appendix M.2.

Between all three conditions, there are three large clusters of sequences (Static AR, Cluster 2 (n=10); Embodied AR, Cluster 3 (n=10); Videos and Figures, Cluster

3 (n=14)) where participants focus solely on the area at work as time goes on and less at other areas such as the step instructions. These outline the cases where participants have learned the step and reduce the reliance on the instructions.

For the sifted sequence diagrams in Figure 6.9, detailed patterns between and within the conditions can be found. In general, there is a large focus on the area of work where users were performing the bead weaving task. Between all conditions (especially Static AR and Videos and Figures), it can be seen there is a greater reliance on learning materials towards the beginning of the stitches which decreases over time (i.e., greater focus on the area of work). This reflects the ability for participants to learn the stitch with a decrease of reliance on the learning materials. Between all conditions, at the end there is a greater increase at out of bounds and video/hands as the participant usually faced the researcher (who is located in the direction to the right of the video/hands) when the trial was coming to an end.

Within Static AR, it can be seen there was an increased focus on the virtual 3D hands at the beginning of the experience however reliance quickly decreases. This illustrates participants gave the 3D hands a chance, however decreased their focus on this resource.

Between Static AR and Videos and Figures, a couple findings can be derived in combination between the sifted sequence diagrams Figure 6.9 and the proportions in Table 6.5. There is a greater proportion of time looked at the 2D video (13.25%, Videos and Figures) throughout the trials in comparison to the 3D hands (2.78%, Static AR). Conversely, there is a greater proportion of time looked at the 3D bead model (8.31%, Static AR) in comparison to the 2D figure (2.39%, Videos and Figures). I compared the proportion of time looked at the 2D video to the time looked at the 3D hands (Static AR). The Z-test indicated that the difference between the proportions of time looked at these learning materials are not statistically significant ($Z = 1.22$, $p = 0.22$). Additionally, I compared the proportion of time looked at the 2D figure in comparison to the 3D bead model (Static AR). The Z-test indicated that the difference between proportions of time looked at these learning materials are also not statistically significant ($Z = 0.83$, $p = 0.41$). As the duration of the video and virtual hand clips could be influential, I derived the total duration of each learning resource based on the start and end timestamps for each step across both stitches. The total

Figure 6.9: Sifted sequence diagrams organized by gaze targets

hand clip duration across both stitches is 608.5 seconds, and the total video duration across both stitches is 495.5 seconds. It would have been expected that virtual hand viewing duration would be greater based on this factor, however the opposite effect was observed.

Within Static AR, there is a slightly larger focus on the area of work (75.64%) in comparison to the focus on area of work in Videos and Figures (70.53%). As the 3D bead model and 3D virtual hands are located in the area of work for Embodied AR, the greater proportion in area of work (85.14%) is expected. Interestingly, the proportion looked at the step instructions is relatively consistent between learning

Table 6.5: Gaze target proportions

	Area of Work	**Step Instructions**	**Model**	**Video/Hands**	**Out of Bounds**
Videos and Figures	70.53%	13.28%	2.39%	13.25%	0.55%
Static AR	75.64%	12.78%	8.31%	2.78%	0.50%
Embodied AR	85.14%	13.83%	N/A	N/A	1.02%

materials: Videos and Figures (13.28%), Static AR (12.78%), Embodied AR (13.83%) which implies the conditions had no impact on the how frequent participants viewed the step instructions.

6.3.2 Interaction Techniques

First, I find that the number of interaction technique events between participants has a high range and standard deviation shown in Appendix M.3. Thus, I opt to compare the proportion of how participants interacted within each trial to give equal weight for each participant instead of utilizing the raw event counts.

As shown in Figure 6.10, the proportions of the interaction techniques from across each conditions are visualized (i.e., a proportion value of 1.0 means that interaction technique was used solely throughout the trial, whereas a value of 0.0 implies that interaction technique was never used). Within each interaction the technique the distributions between conditions are similar, especially between Embodied AR and Videos and Figures. Static AR tends to have a lower average proportion using voice commands, and a higher average proportion using gaze in comparison to the other conditions. Between the interaction techniques, it appears if voice commands are used as a higher proportion between all conditions. Followed by gaze and then touch as the lowest.

Using the Shapiro-Wilk normality test ($\alpha = 0.05$), I found for which interaction technique proportions I can assume a normal distribution in Table 6.6.

I used the Kruskal-Wallis test to evaluate the differences across the three learning materials for bead weaving on the interaction techniques as they did not follow a normal distribution.

No statistically significant differences were found between the learning conditions on: voice ($\chi^2 = 3.50, p = 0.17, df = 2$), gaze ($\chi^2 = 3.84, p = 0.15, df = 2$), and touch

Table 6.6: Normality of interaction technique proportions

Interaction Technique Proportions	**Shapiro-Wilk Normality Test** (Alpha = 0.05)		
	Test Statistic (W)	p-value	Conclusion
Voice	0.79	6.55e-8	Non-parametric
Gaze	0.85	0.00	Non-parametric
Touch	0.77	3.25e-8	Non-parametric

$(\chi^2 = 3.07, p = 0.21, df = 2)$.

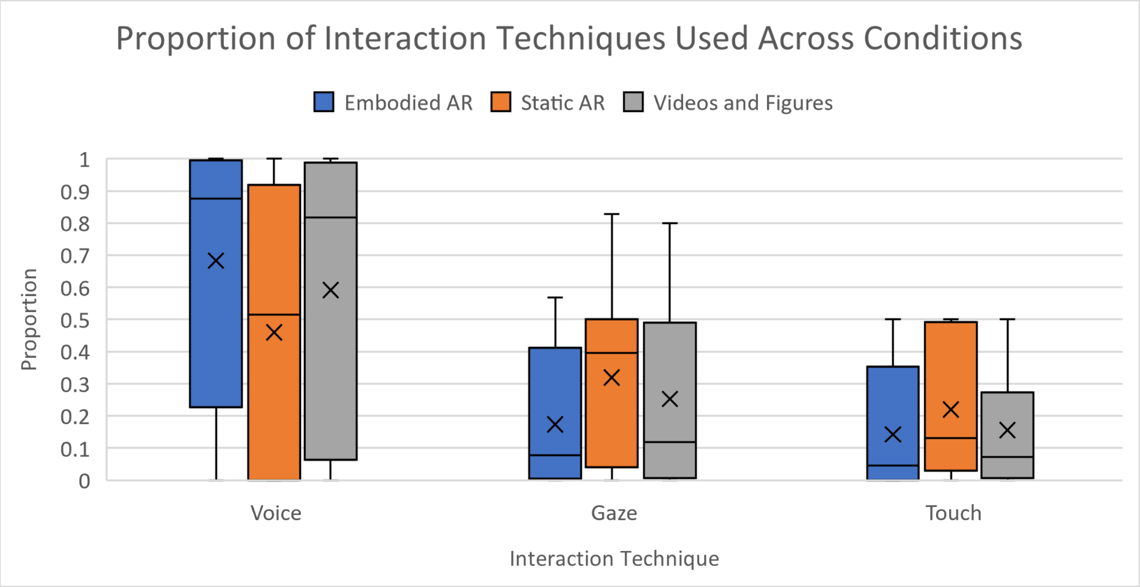
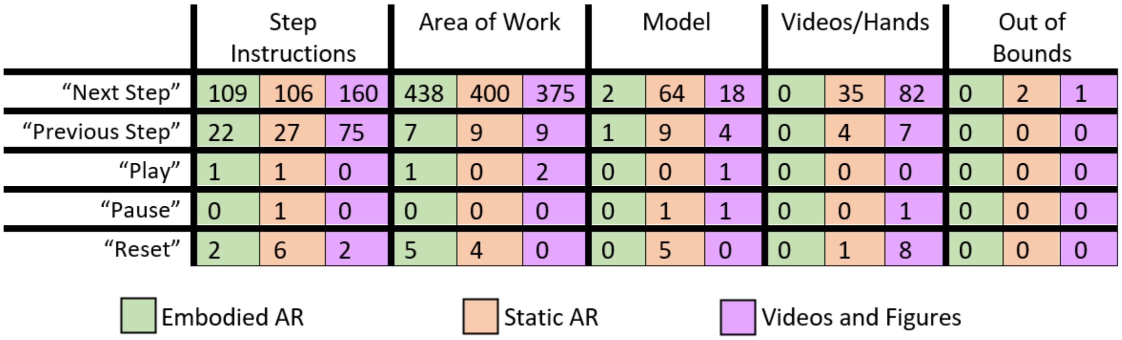


Figure 6.10: Proportion of interaction techniques used in the trials

Focus of Attention of Voice Commands

As users have to look at the button for gaze and touch interaction events, we assume they would be looking at their target. However, for voice commands no visual target is required. Figure 6.11 displays the tally of voice commands with their visual targets across the three different conditions.

From a total of 2009 voice command events, majority of the voice commands used are the “Next Step” voice commands (89.2%, 1792/2009). This is followed by the “Previous Step” voice commands (8.66%, 174/2009), with a surprisingly low number of “Play” (0.3%, 6/2009), “Pause” (0.2%, 4/2009), and “Reset” (1.64%,



	Step Instructions			Area of Work			Model			Videos/Hands			Out of Bounds		
"Next Step"	109	106	160	438	400	375	2	64	18	0	35	82	0	2	1
"Previous Step"	22	27	75	7	9	9	1	9	4	0	4	7	0	0	0
"Play"	1	1	0	1	0	2	0	0	1	0	0	0	0	0	0
"Pause"	0	1	0	0	0	0	0	1	1	0	0	1	0	0	0
"Reset"	2	6	2	5	4	0	0	5	0	0	1	8	0	0	0

🟩 Embodied AR 🟧 Static AR 🟪 Videos and Figures

Figure 6.11: Voice command visual target frequency matrix

33/2009) voice commands. This suggests for voice commands, the "Next Step" and "Previous Step" had much higher utility than the learning material control voice commands (e.g., "Play", "Pause", and "Reset"). As the system segments the learning materials to smaller chunks via the step-by-step design, these results align with the expectations set by Yamaguchi et al. [86] that the participant would require less interaction pausing/playing the dynamic learning material.

Interestingly, for the 1792 "Next Step" voice command events, only 20.9% (375/1792) of the events occurred with a focus on the step instructions, whereas 67.7% (1213/1792) of the events occurred with a focus on the area of work, with a similar distribution across all the three learning conditions. Conversely, for the 174 "Previous Step" voice command events, only 14.4% (25/174) focus on the area of work, whereas 71.4% (124/174) focus on the step instructions. This suggests participants would focus on their area of work when iterating to the next step, however when wanting to return their attention would be focused on the step instructions.

There are a couple interesting comparisons within the conditions as well. For the "Next Step" voice command between the Static AR and Videos and Figures, there is a tendency for participants to look at the Model in Static AR and a similar tendency for participants to look at the Video in Videos and Figures. Although this observation comes with limitations as it is based from a small sample of the entirety of the "Next Step" voice command events.

From the 174 "Previous Step" voice commands, interestingly 54.6% (95/174) were from the Videos and Figures condition, whereas only 28.2% (49/174) were from Static AR and 17.2% from Embodied AR. This suggests for the traditional videos and figures that more participants went back to the previous steps in comparison to the AR conditions.

6.4 Beadwork Analysis Results

6.4.1 Quality Ranking

The two expert craftspeople both independently ranked the beadwork. The resulting rankings were merged and visualized in Figure 6.12. Furthermore, similarly ranked stitches are placed to the left and the conflicted rankings are visualized within boxes spanning the differing ranks; these are further labeled and color-coded to identify which expert ranked it higher or lower. Note that full resolution images of the presented beadwork are available in Appendix K with the detailed rankings located in Table 6.7. From the first pass of ranking, the experts similarly ranked 56.67% (17/30) of the netting beadwork and 76.67% (23/30) of the peyote stitch. The rankings that differed were by a factor of 1, except for 1 ranking which differed by a factor of 2.

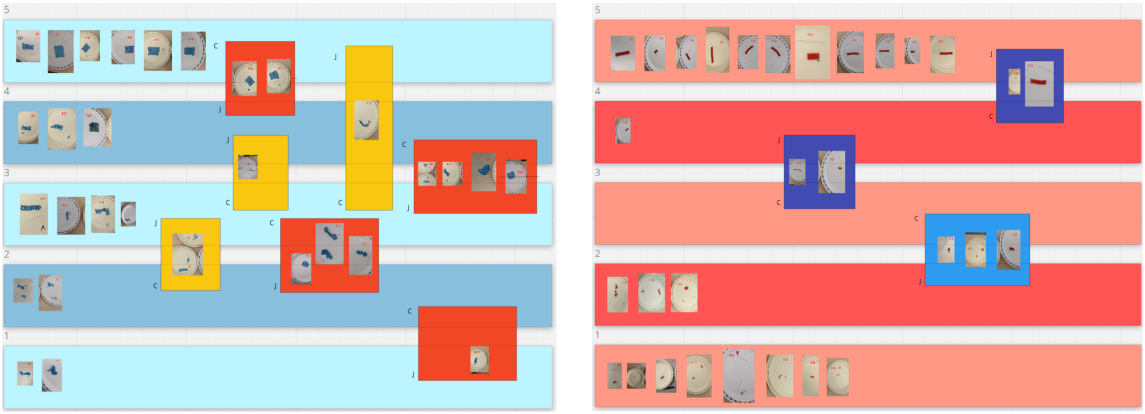


Figure 6.12: First pass expert beadwork rankings. Left: netting beadwork rankings. Right: peyote beadwork rankings.

Through the meeting with both craftspeople, we discovered a set of extra considerations that impacted the ranking process. These include:

- Extra loops on the stitch, a tension between if extra/less loops should penalize the quality of the beadwork even if they match the stitch. (E.g., if the generated netting stitch were 6 sections wide instead of the pictured 4 section wide piece).

Table 6.7: First pass beadwork rankings

Rank	**Netting Stitch**		**Peyote Stitch**	
	Expert 1 Ranking	*Expert 2 Ranking*	*Expert 1 Ranking*	*Expert 2 Ranking*
5	P3, P9, P10, P12, P14, P17, P20, P28	P3, P9, P10, P13, P14, P17, P28	P3, P5, P8, P9, P10, P12, P14, P17, P20, P25, P28	P3, P5, P8, P9, P10, P12, P14, P15, P17, P20, P23, P25, P28
4	P5, P19, P21, P24, P25, P27, P30	P5, P12, P20, P23, P27, P30	P15, P23, P24	P22, P24, P27
3	P4, P13, P15, P16, P18, P23, P26, P29	P8, P15, P19, P21, P24, P25, P26, P29	P1, P21, P22, P27, P29	
2	P1, P8, P11, P22	P1, P4, P6, P11, P16, P18	P7, P19, P30	P1, P21, P29
1	P2, P7	P2, P7, P22	P2, P4, P6, P11, P13, P16, P18, P26	P2, P4, P6, P7, P11, P13, P16, P18, P19, P26, P30

- There is tension with the quantity that is done, such that the instructions could be followed properly but the beadwork not be as developed as others.
- If there are multiple presented pieces of beadwork, how to judge the quality of the work. Subconsciously, one expert did the average of the presented pieces.
- Primarily for the netting stitch, unsure to what degree the color of the beads. For low ranking beadwork, there is indication participants achieved the color pattern correctly but not the stitch correctly.

Throughout the discussion process, the experts revealed they mostly agreed with the other expert's scores given their assumptions on the above considerations. The other cases were slightly different perspectives on how they interpreted the ranking scale, as they noted it is subjective what they would classify as an error versus somebody else. Additionally, if the expert has done the technique before they have a background on it which could inform how they see the piece in comparison to strictly comparing the generated work to the reference image. Lastly, there were some noted limitations such as the photographs may be hiding errors on the back of the stitch they could not be seeing (e.g., overlapping threads), and suggested clear beads to see what the thread was actually doing in the structure.

Following the discussion, I compiled the above reasons from the meeting, and determined which assumptions would be more suitable for the evaluation of the beadwork for the context of this study. The selected assumptions are as follows:

- Regarding the extra loops, the beadwork should be penalized if it does not match the specifications of the learning instructions. While they may be learning the stitch, by having variation from the learning material it indicates it not being properly followed.
- Regarding the tension between how much is done, that should have an impact on the scores generated. Due to the design of the study, each participant had similar time available to work on these stitches. It is indicative of how well the learning instructions can be followed.
- Regarding multiple pieces, the average should be used. This is due to the earlier beadwork being representative of the mistakes carried through from the learning material.
- The color pattern should have some impact on the ranking, as it indicates how well participants followed the stringing steps rather than only the threading steps.

Using the given assumptions, I parsed through the tiebreakers and applied the rules given to partially determine the scores. In addition, I considered the reflection of their scores from the meeting process if the experts were swayed to re-assess their scores. In most cases, the scores were not swayed and thus used the above rules as the primary means for determining the final ranks. In cases where there was no agreed conclusion with the above assumptions, the average of the values were used. Notably, the application of the rules resolved 85% of the tie breakers (17/20), where only 3 tiebreakers remained within the netting stitch rankings. This is likely due to increased complexity of the netting stitch. Thus, the average of the two scores were used for the 3 remaining ties. The finalized rankings are presented in Table 6.8 and Figure 6.13.

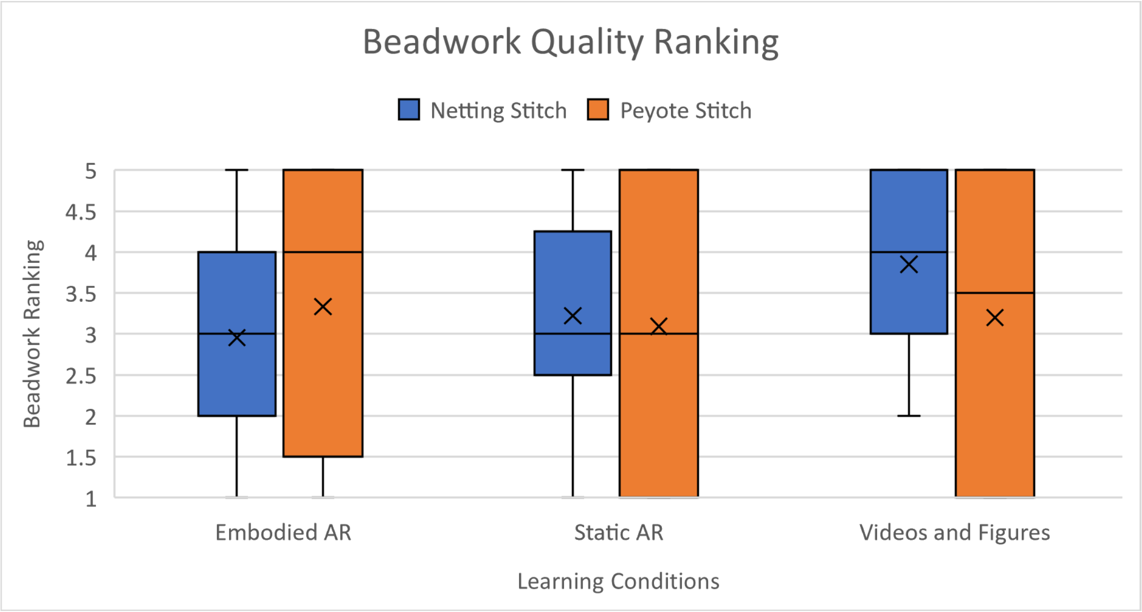


Figure 6.13: Finalized beadwork rankings

From Figure 6.13, it can be observed the distribution of peyote rankings are relatively similar. The average scores of the peyote stitch are as follows: Embodied AR (3.33), Static AR (3.09), and Videos and Figures (3.2). However, for the netting stitch beadwork, there is a relatively more concise distribution in comparison to the peyote stitch beadwork distribution. The Videos and Figures tend to have a slightly higher distribution of ranks in comparison to Embodied AR and Static AR, with the average scores of the netting as follows: Embodied AR (2.95), Static AR(3.22), and Videos and Figures (3.85). I used two-way ANOVA to determine if there was a significant difference between the learning conditions and stitch type with regards to the beadwork rankings. No statistically significant differences were found between learning conditions and stitch type on the beadwork rankings as observed in Table 6.9.

6.4.2 Measure of Work Analysis

The number of beads from each condition for the peyote and netting stitch beadwork is illustrated in Figure 6.14. It can be seen that the netting stitch on average has more beads than the peyote stitch. This result is expected as the netting stitch requires more beads for the stringing steps.

Table 6.8: Finalized beadwork rankings

Rank	**Netting Stitch**	**Peyote Stitch**
5	P3, P9, P10, P14, P17, P28	P3, P5, P8, P9, P10, P12, P14, P17, P20, P25, P28
(4.5)	P20, P12	
4	P5, P27, P30, P13, P21	P24, P15, P23
(3.5)	P24	
3	P4, P15, P26, P29, P23, P16, P25, P19	P22, P27, P1, P21, P29
(2.5)	P18	
2	P1, P11, P8, P6	P7, P19, P30
(1.5)		
1	P2, P7, P22	P2, P4, P6, P11, P13, P16, P18, P26

Table 6.9: 2-Way ANOVA results on beadwork quality rankings

	Df	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Stitch Type	1	0.27	0.27	0.12	0.73
Learning Condition	2	2.02	1.01	0.45	0.64
Residuals	56	125.45	2.24		

Using the Shapiro-Wilk normality test ($\alpha = 0.05$), I found for which beadwork I can assume a normal distribution in Table 6.10.

For the netting stitch I used one-way ANOVA to evaluate the differences across the learning materials for bead weaving on the netting stitch as it followed a normal distribution. No statistically significant differences were found between the learning conditions and the measure of work for the netting stitch (F(2,27)=1.84, p=0.18). The means and standard deviations for each learning material during each stitch can be found in Table 6.11.

For the peyote stitch I used the Kruskal-Wallis test to evaluate the differences

Table 6.10: Normality of beadwork measure of work done

Beadwork Measure of Work	**Shapiro-Wilk Normality Test** ($\alpha = 0.05$)		
	Test Statistic (W)	p-value	Conclusion
Netting Stitch	0.95	0.16	Parametric
Peyote Stitch	0.90	0.01	Non-parametric

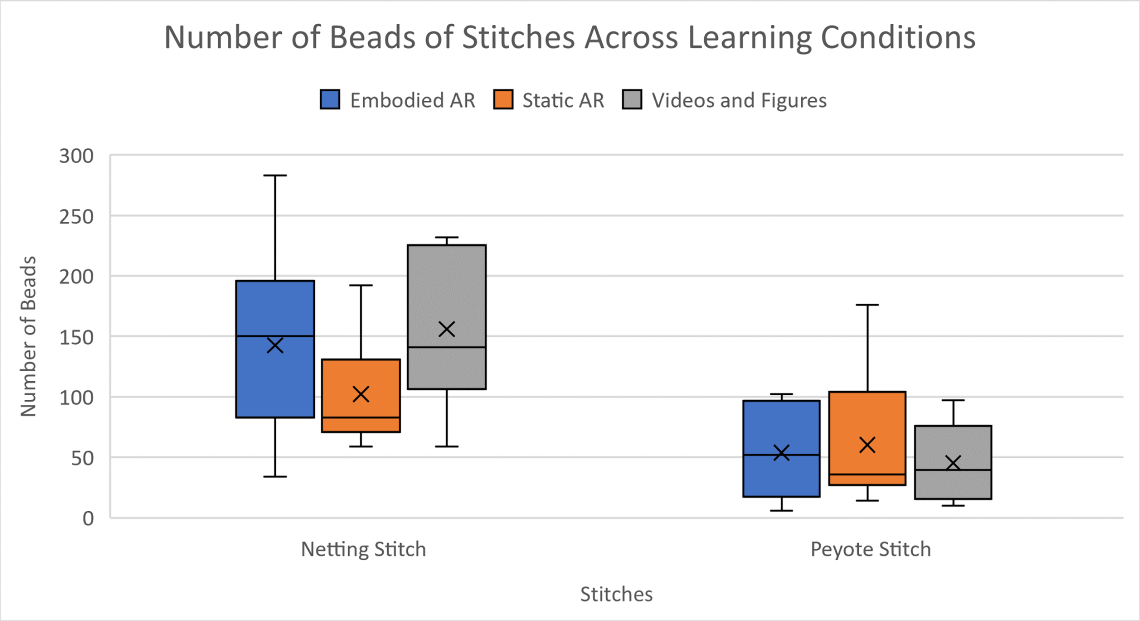


Figure 6.14: Beadwork measure of work done by number of beads

Table 6.11: Mean and standard deviation of beadwork rankings

Learning Condition	**Netting Stitch**	**Peyote Stitch**
Embodied AR	M = 2.95, SD = 1.42	M = 3.33, SD = 1.80
Static AR	M = 3.22, SD = 1.22	M = 3.09, SD = 1.70
Videos and Figures	M = 3.85, SD = 1.06	M = 3.2, SD = 1.69

across the three learning materials for bead weaving on the peyote stitch as it did not follow a normal distribution. No statistically significant differences were found between the learning conditions and the measure of work for the peyote stitch ($\chi^2 = 0.51, p = 0.78, df = 2$).

6.5 Interview Analysis Results

Following are the results found from each category.

6.5.1 Preference of Learning Bead Weaving Between Trials

For these results, participants indicated which trials they preferred. In raw numbers, 12/20 preferred Videos and Figures, 10/20 preferred Static AR, and 8/20 preferred

Embodied AR. In terms of raw number of order, from the trials preferred 9/30 preferred the first encountered trial learning settings and 21/30 preferred the second trial encountered learning settings. Lastly, in terms of the stitch involved with each learning condition, 10/30 preferred learning trials that involved the peyote stitch, and 20/30 preferred learning trials that involved the netting stitch.

6.5.2 Guidance Participants Found Helpful in AR

There was a large variation in what people liked, however 20/30 liked the 3D bead model for the reasons:

- Perspective, this is illustrated by P20, ”I liked the on the hand it gave you like you could see it and you could see different angles, as opposed to like the picture was just static like in the first one”.
- Clarity, this is illustrated by P30, ”I like the fact that it’s really like there’s no background in it or anything. It’s just like a graphic of beads and the hand gestures and the and the threads. So it’s like a really magnified version of what you’re trying to focus on. I found that pretty helpful”.
- Integrated beading actions, this is illustrated by P29, “So for example, the way the needle had to point for example. So it was very obvious what to do with the 3D model. Whereas with the lady with the person explaining it, it was more I-I had to use a diagram as well. So the 3D model sort of had both the diagram as well as the motion itself, had both of them combined together so I thought it was like super useful at the time”.

Participants also liked the videos and images. The video provided context from an actual bead weaver as illustrated by P17, “Because I could actually see that the woman was doing with her hand and you know specifically with this [netting], because there were a lot of beads to weave in one go and you had to actually see which beads to you know put your needle, pass it through to make a new row. So that was easy to understand, looking at the video, if it had been the hand gesture or the diagram, it would have been a little difficult”.

A few participants mentioned they liked the 3D hands, however P16 thought it would be more suitable for general hand movements: “I mean, if it wasn’t about needle threading, I can see the first one being like the hands and the gestures and that being a lot more useful. … Mostly teaching stuff like teaching basic tasks to, especially kids. My brother is autistic, and I know it took us a while to explain to him how to hammer stuff in and this can be a great example of that".

While less important for the research questions but important for justifying the design choices, participants also enjoyed the broken-down step-by-step process provided by the system. This is illustrated by P9, "I thought like the voice commands and the pattern written out was helpful like especially for the second one, it was easier to reference that versus if you were just watching a video, like having to pause and go back and figure it out. Like I liked having the pattern on the screen".

6.5.3 Guidance Participants Found Not Helpful in AR

There was an overwhelming majority of participants who found the 3D hands not helpful due to the lack of context working with the beads. They were able to understand the hand movements, however for learning bead weaving, the lack of context with the beads resulted in a lack of helpfulness. This is illustrated well by P25, "I didn't really find the hands useful because I saw there was motion, but then it wasn't really attached to like the beads strings in AR, so since it was completely separate, I just didn't like feel the need for it and just looking at the picture in AR and the direction that it gave was good enough … I think if, you incorporated the hand model with the beads. Then maybe that would be more helpful, but then I'm not sure because then there might be some like 3D overlap or something which might cause problems".

Another notable issue found in the Embodied AR condition is that the 3D hands would often interfere with their own work and a suggestion from P6 includes: "if you could move it a little bit upwards or downwards if you did this, then it would be really helpful and it would not interfere with my actual beads".

There were a couple of participants that found the video not helpful, as it lacked similarity to their beads, perspective, and they have to stop/start it. This is illustrated by P28, "It was like mine didn't look exactly like it, so it's like hard to follow where and you couldn't really see how this string was supposed to be going where it is in the guide on the left you can see like exactly where this string you've been and where it's going and stuff like that. And if I was like looking down then looks up and I kind of missed in the video what was going on and I'd have to keep replaying. Whereas just looking at the guide in the left I can see where this thing is going".

6.5.4 Design Feedback

3D Bead Model (Embodied)

13/19 participants found the 3D bead model helpful in aiding them to complete the bead weaving tasks.

There are mixed feelings regarding the model being anchored above the left hand. Participants liked it following their hand for the reasons:

- they could flip it up when they needed it,
- were able to manipulate it to show multiple perspectives,
- they liked it being close to their work, they could reference their own work while viewing the model.

This behaviour is illustrated by participant 18: "I could just focus on my hands and focus on the task at hand without having to move around and look up and it just help me stay focused on the task having everything in one vision and one view".

However, there was other participants who had criticisms with the anchored above the left-hand placement:

- it was tiring to lift their arm,
- distracting to move their hand that much,
- the position was too low for use or undesirable angle.

This behavior is illustrated by participant 10, "I could have probably taken more time to stop and look at it the way I wanted, but I found it kind of hard to, or maybe distracting when it was just moving my hands that much".

One participant suggested a mixed approach, by being able to manipulate the model to gain perspectives and fixing it when no longer needed.

3D Bead Model (Static)

12/20 participants found the 3D bead model very helpful. In two cases where participants did not notice the model, they were failing to properly complete the stitch, only once they noticed the model were they able to succeed.

Participants liked how it visualized the progress of the steps and showed the direction and path taken by the needle through the beadwork. It was useful for comparing their own beadwork to the model for discrepancies.

Nine participants noted that the model was helpful as is, however there were aspects it lacked. A lack of control allowed for limited views, this is illustrated by P13 “I think the only thing I felt was that if we could have seen the complete 360-degree view of that beads because I felt that I wasn’t able to see the back and how the thread is going from that side. So I thought maybe a 360 degree kind of view rather than just a single kind of view, that could have been better”.

14 participants liked the position of the bead model as it was separated from all the other learning materials so they could focus on it, and the remaining participants found it cumbersome or too far from other learning resources they wanted to reference together. The tension between the placement is illustrated by P5, ”there was a certain aspect of it was very helpful to have it right there and know where it was at all times and get a good view of it. But not having it in in the same area as where I’m doing the work meant that if I if I was unsure or something I would have to constantly be checking back and forth”.

2D Figure

14/20 participants found the 2D figure to be helpful in learning bead weaving. Aspects that were helpful include:

- The figure helped to determine what step the participant should be on and when to progress to the next steps. This is illustrated by P9, “that was good for like understanding exactly where in the piece you should be and following like what step you’re supposed to be on”.
- They could compare the figure to their work to identify issues and determine solutions. This is illustrated by P4, “I realized I messed up at one step by

seeing the image. So that so yeah, for that it was really helpful to monitor what I was actually doing and if I'm reaching the correct step or if I'm doing this step currently, if I got the end result as expected".

However, there were also aspects that were found to be not helpful:

- The figure requires frequent comparisons with their own work. This can be cumbersome when distance between their own work and the figure is large. This is illustrated by P5, "it was nice, but again as same as single problem first, having to look back and forth if you were unsure of something".

- Difficult to determine how you reach the product showed by the figure. This is illustrated by P8, "diagram just shows you a picture . Sometimes you don't understand how to go in the diagram" and P15 "So in the 2D figure, initially I was a little bit confused how exactly I need to know how exactly I need to proceed to the next step and how exactly need to like insert the needle to be next available like bead".

- Difficult to determine how the figure grows, this was illustrated well by P10, "it was good at the start, but once it had a couple beads on, there was hard to see to figure out where the string was going for me".

3D Hands (Embodied)

All participants did not find the hands useful for a range of reasons:

- Missing context; suggested integrated bead model despite the integrative elements in my design intended to connect the two 3D representations. This is illustrated by P4, "I really liked the movement of the hand, but if the if the beads and thread had followed and if it was fluid like how it was shown in the video, it would have been much better".

- Blocking vision of four participants. This is shown by P12, "because when I was trying to do the beading, I was seeing the hands there and it was actually hitting my eyes and I had to move around to see the actual stuff because this was covering my eyes".

- Did not understand hand movements. This is shown by P16, “I couldn’t understand half of the motions”.
- The hand movements were not helpful, they were able to derive hand movements themselves. This is illustrated by P25, “I think like I was able to figure out the movements myself, but I don’t think the hands helped me really”.

3D Hands (Static)

15/20 participants found the hands were not helpful for similar reasons as the embodied 3D hands. Interestingly, there were no instances of blocking vision, however there were instances of difficulty understanding how the hand movements were related to the environment. These include:

- Missing context; suggested integrated bead model despite the integrative elements in my design intended to connect the two 3D representations. As shown by P17, “it was showing like move needle like this and just pick up one beads so I couldn’t understand, I picked up the bead but where do I move the needle? There was no thread and there was no there was no reference to be clear like where to move the needle and what to do next. So that was one thing I disliked about it was very confusing and it would have been better as I said if it had showed me the bead and needle and thread as well for a reference”.
- Did not understand how hand movements applied to work. As shown by P30, ”I think it showed the hand motions you’re supposed to do, but it doesn’t show you like what the hand motions are supposed to do to the to your work”.
- Difficult to understand what hands are doing in relation to environment. As shown by P5, ”the problem with it [3D hands (Static)] is it’s sometimes hard to tell exactly what the hand is, the hands are trying to motion towards”.

It is interesting that there were two instances of positive feedback given for the hands while they were positioned to the right. One participant found the perspective of the hands may have attributed to being able to derive meaning from them. Examples include:

- From P25, “Yeah, it kind of gave me like a base ground of like how I should start or like yeah where I should start my hands and like where my fingers should start to go so it’s served as a good baseline”.
- From P7, “That’s where I learned that you can use the back of hand to keep all the strings untangled”.

Video

14/19 participants liked the video, however there were both benefits and issues associated with the video representation.

The benefits include:

- Better progression within the step, shows *how* to do it. This is illustrated by P20, ”you could sort of see what the pattern was supposed to look like as it [the video] progressed better, than with the single stitch in the picture”.
- Familiar representation as described by P21, “I just felt I think we are used to watching a lot of YouTube tutorials so there was some sort of bias also, I was used to those videos so I could quickly grasp what they were saying”.
- Realistic view of beadwork as described by P28, “the diagram was kind of like idealistic of what we want it to look like, but the video gave you much more to like I looked up ’cause I’m like. This looks nothing like the diagram, but I looked at the video and it’s like oh looks more like that. So I felt more confident seeing that it’s like not going to be perfect”.

The issues include:

- Unclear at times, as described by P29, “how the beads should look was not very apparent to me. So I guess there’s a lot of distraction. There’s a lot of noise that wasn’t there in the other model”.
- Hands occluding information, as described by P27, “it was like kind of hard to tell sometimes because of like the hand covering the beads. It was hard to tell like which one to loop through I guess. So like I refer to the diagram, the most for in terms of like looping through which bead”.

Purple Guidance Trail (Weaving Operation) [Beads or Hands]

17/30 of the participants found the purple guidance trail useful on the 3D bead model, but not on the 3D hands. For the 3D bead model, it showed which bead to thread through, as illustrated by P8 who was able to complete their stitch due to the additional guidance that was not offered from the traditional 2D figure in their first trial, “because that exactly showed where to go. I mean which way where the thread should go that that because that way you know I got this perfectly this time”.

Three participants found that the 3D purple line in the 3D model was more useful for the 5-bead netting stitch as opposed to the peyote stitch. This is illustrated by P12, “that purple thread helped me to understand which bead I need to start with, and that was helpful in the first one [netting stitch] especially because it first one felt a little bit complicated when compared to second one [peyote stitch], not so complicated but once to get that you know square boxes, exactly, the random squares, it was helpful with the purple thread because the thread showed exactly which one I need to get along so that I will get the pattern properly”.

One interesting observation is that the hand movements involved are indicated from the 3D bead model, this is illustrated by P3, “how the string like for the purple trail for the first task that was on the left side, it actually showed how you should move your hand. It didn’t show your hand, but it was obvious how it is going to go, so I think it was very clear and very easy to understand”.

The concerns for the purple line with the 3D hands arose from the lack of additional context of the beads. This is illustrated by P19, “I did not find it helpful because, in that beads were not shown, it was just a purple thread. I was not knowing that to the left of that thread to the right of that thread, how many beads are there from which position it is passing. So, if some beads are present around it and that purple thread is there, then it’ll be helpful compared to the present one”. The purple trail was not that helpful for the actual bead weaving task as illustrated by P24, “it kind of just showed the gesture but not where the position should go. So, the positioning was absent in there so that kind of gave me a step back . . . Backward or forward, the direction was there, but the position of the beads weren’t in there”.

Six participants did not notice the correlation of the purple line between the 3D bead model and the 3D hands for both the conditions (Embodied AR and Static AR).

This could attribute to the lack of helpfulness for the purple trail in respect to the AR hands.

Presence of Beads and Needle in Hands (Stringing Operation)

Four participants found the stringing action to be simple or too slow and did not require additional visualization. This is described by both P25 and P30 respectively, “that was good, but because I noticed that just for like stringing a bead, I thought that was pretty self explanatory and like that’s something I guess nice to have to show but like not really needed” and “I thought that part was a bit slow. Like for example would say string of B bead and A bead. I mean, if you just remember the sequence. It’s not that difficult to remember the sequence, but then the visuals are kind of just slow”.

There were others who did like seeing how the beads got picked up as it showed how experienced craftspeople pick up the beads. This is described by P6, “in the first task I wasn’t able to see how they were beading, so I had to use both of my hands for the first task and the second task when I saw that they are stringing the beads in that way, I followed them and then it was- then I picked up the speed to string the threads”.

10 participants did not notice the stringing action. This could be caused at what state of the step the participant observed the hands (i.e., if the participant did not look at the hands at the beginning, they would have missed the stringing action). This is illustrated by P18, “when I looked at it I was already in the middle of the instruction being repeated. So it was already in the middle of doing the action. So I must have missed it loading the beads in” or due to the lack of attention to the hands due to the perceived unusefulness such as for P14, “I’ll say, I did not follow the hands much”. Another possibility is due to the size of the needle and beads, as illustrated by P11, “since it was a bead weaving task the size of needle and bead was smaller, much like it was much more smaller than the hands. So I have to like look carefully with the direction because it was a small things right as compared to the hands or the picture of the hands were like much more bigger”.

Some participants got confused where the beads went once the stringing action was completed such as P17, “I saw that 3D model and I picked up the beads looking at the 3D hand gestures, but after that I got confused like where are the beads going? What do I do next? So that's when I reference the 3D model".

Sliding Bead Animation on Model

26 participants enjoyed the bead sliding on the 3D bead model as it:

- Relaxed the pace, as described by P3, "If the animation wasn't there, and it was just like the accomplishment of the task without just showing the animation, it would have been 'OK, I should hurry now' But now that it's starting, you can take your time, it's going down, I think it's going down, I think it's it gives you a better feeling".

- Gave them confidence in their actions, as described by P19, "sliding is helpful rather than just showing up. If it is sliding, subconsciously we will be like yes, we are following the exact thing, if without sliding pattern is shown up we will be like oh how this pattern came up".

- Identified which beads to string on, as described by P12, "if it was another case where the sliding wasn't there, then I might have got confused like where are the beads because in the figure it is showing the beads but in the needle there are no beads but the sliding helped me to actually tell that OK I need to add a couple of more beads and then I'll get the pattern".

Four participants thought it did not help them learn as it seemed obvious to them, P17 "[They liked] Nothing in particular. I mean it was, sort of natural for me to put the beads on the needle and they would naturally slide down".

Interaction Techniques

While finding the proportions and reasons of which interaction technique are useful to address issues in the literature, they are not directly related to my research questions. Thus, the results for this can be found in Appendix M.4.1.

6.5.5 Which Stitch Was More Difficult and Why

When prompted which stitch is inherently more difficult, 14 out of 30 (46.67%) participants reported peyote was more difficult and 16 out of 30 (53.33%) participants reported netting was more difficult.

Peyote was found to be more difficult than netting as it lacked color differentiation, beads were too close together (i.e., harder to manipulate), and beadwork was more difficult to do correctly. Netting was found to be more difficult than peyote as it had more complex steps, more colors to keep track of, it was easier to make mistakes, and harder to maintain tension.

6.5.6 Strategies Built

These results are not directly related to my research questions, but are still relevant for considering ongoing use of the learning materials (e.g., a source of design insight). The built strategies can be found in Appendix M.4.2.

6.5.7 Ideal Learning Resource

Due to the exposure of different learning resources depending on which two trials the participant encountered, this subsection is broken down into 3 smaller sections relating to each pair of conditions. However, it is important to note these results come with limitations as some learning materials are not direct alternatives due to different levels of context available within them.

Embodied AR vs Static AR

I compare how participants want the 3D bead model and 3D hands positioned. 3/9 participants wanted the 3D bead model on the left, 3/9 participants wanted it to follow their left hand, 1 wanted it to the right, 1 in front of them, and 1 did not want the 3D bead model. For the 3D hands, eight participants leaned towards having the hands in front of them, although shifted out of the way where they were working with the beads. In addition, participants requested the beadwork to be integrated with the hands.

Static AR vs Videos and Figures

I compare what learning materials participants prefer. Comparing the 3D bead model and the 2D figure: 9/10 participants preferred the 3D bead model, 1 wanted both the 3D bead model and 2D figure, and one wanted only the 2D figure. This shows a preference towards the 3D bead model over the 2D figure. Comparing the 2D video and the 3D hands: 7/10 participants wanted the 2D video, whereas 1 wanted the 3D hands and 2 did not want either. Nine participants indicated interest in keeping the audio/text as well.

Embodied AR vs Videos and Figures

I compare position and learning material between Embodied AR and Videos and Figures. All participants liked the 3D bead model and preferred the positioning: on hand (2 participants), to the left (6 participants), in front (5 participants), or to the right (1 participant). 2/9 participants wanted the 2D figure in addition the 3D bead model, and wanted the figure out of the way while the bead model on the hand or on the right. 6/9 participants liked the video, interestingly either on the right or in front of them, but not at the area of work. Only (1/9) liked the 3D hands, but requested them close to the beads.

6.5.8 Text and Audio Step Descriptions

Six participants listened to the audio while focusing on the beadwork, and then referenced the text above when necessary. This is illustrated by P9, “I like the audio because it meant that I didn’t have to look up and down every time, but I was happy that the text was there for me to reference”. Participants generally liked the text to display the beading pattern for stringing new beads. This is shown by P23, “they both helped me, especially during second one when it was more about which beads should be given first and then second ABB ABB”. Five participants preferred the text to the side as it was used for a reference rather than the primary focus for instruction. This is shown by P29, “I knew what the text is going to look like, and so the steps are very repetitive. I don’t need those to be the focus anymore. So they can be towards the side”.

6.5.9 Hand Position Preference

Four participants mentioned preferring the hands far away and six mentioned preferring the hands close to them.

They liked the hands far away because:

- The hands were less useful and did not need to be the focus.
- It blocked their vision, as the hands were interfering with their beadwork.
- Got distracted while it was moving while they were trying to work on their task.

They liked the hands close because:

- Less eye/neck strain as they did not need to turn their neck/head to focus on hands. One participant brought up the concern of field of view limitations.
- More realistic, it matched their perspective of their hands while they worked. This is illustrated by P30, "I think having the hands in front of me would be more relatable … If it was just right where my hand position was, it's easier to like mimic the, the tutorial with my own hands".

6.5.10 Bead Position Preference

Six participants preferred the 3D bead model to be stationary and seven participants preferred them to follow their hand.

Those who preferred stationary had the following reasons:

- No distraction from their task, as illustrated by P12, "so firstly not in front of my eyes because that was actually making it uncomfortable to see these things. But the ones which were on left and right they were good like that's how it should be. I don't need to put a lot of effort, I just need to see and I was able to do it".
- Could concentrate on beads individually from other learning resources.
- Less hand/arm strain to lift it.
- Only one perspective that seemed helpful, and that is head on.

Those who preferred it following their hands:

- Less neck/head strain, as illustrated by P18 “I’m already looking at my hands anyway, it’s much more efficient and easier on my neck I guess to just move my arm up and look at what I’m supposed to be doing”.
- Quick to reference as they focus on their hands anyways, as illustrated by P25, “yeah, so it was more accessible and faster that way, but then also again the downside was like kind of lifting my hand a little bit tiring sometimes if I need to look at it often”.
- Allowed for multiple perspectives which aided in problem solving, shown by P30, “it would be nice to have like a different perspective if you get stuck. If you want to see the back backside of the beads”.
- Easier to compare the instructional model with their own model as they did not need to manipulate their real work as illustrated by P14, “so I have to again change my physical model, whereas in the 3D hologram I could manipulate the hologram itself and not change my physical model because that will again confuse me a lot”.

6.5.11 Hands vs Video

14 participants mentioned that they preferred the video as they did not derive meaning from the hand movements as illustrated by P22, “I didn’t understand the motion of it [3D hands] so, but the video it was pretty self explanatory”.

The reasons for preferring videos include:

- Context of the beads, realistic view of the work context, as illustrated by P17, “for a video, it was easy because I could reference it, you know, and compare it to real life”.
- Familiarity of the learning material, as sown by P21, “and probably it was a familiar setting because it was someone doing that, so there was some sort of cognitive bias”.

Three participants preferred the hands for the following reasons:

- Perspective, as it looked like their hands more so than the video. This is illustrated by P26, “it’s all hands only and it’s like bead weaving, watching our own hands through that”.

6.5.12 3D Beads vs 2D Figure

16 participants preferred the 3D model over the 2D figure for the following reasons:

- Realistic, more comparable to their own bead representation as shown by P21, “so the strength for the 3D model was that it was in 3D, so the beads looked as close to what it is in real life”.

- Perspective, could view more angles of the bead representation as illustrated by P20, “you could look at it from different angles and you could see I feel like it showed the string more clearly because it actually like went through the beads”.

- Threading action was easier to understand (purple guidance trail).

The three participants who preferred the 2D figure over the 3D beads had the following reasons:

- Greater familiarity with 2D figures, as demonstrated by P27 “But overall, I did prefer the 2D more. Maybe like I’m more used to that”.

- A simpler representation which made it more accurate.

6.5.13 Workflow and Interface Feedback

When participants reached proficiency with the stitch, in some cases they stopped interacting with the system altogether while working on the beadwork. When prompted during the interview about their reasoning, responses generalized to having sufficiently memorized the stitch and they no longer needed the learning resource. Throughout the trials, all participants kept the AR headset on, however if given the option would have removed it once they were comfortable with the stitch. Some of the participants indicated they would have put it back on if they got stuck, or would have left it on if there was an indication of progress for a larger piece.

I received positive feedback on varying aspects of the system as a whole. While not pertinent to the comparative aspect of the research questions, it aids in validating the design choices made. These can be found in Appendix M.4.3.

6.6 Summary

From the SUS and NASA-TLX scores, there were no statistically significant differences between the learning conditions (Embodied AR, Static AR, and Videos and Figures). For the learning material helpfulness, there were significant differences between the helpfulness of the virtual hands being lower than other learning materials; no significant differences were found between helpfulness within the condition pairs. The bead weaving experience results tended positively across all learning conditions. From the sequence diagrams of the gaze targets relationships emerged. There are no statistically significant differences between the interaction techniques used and the learning conditions, however similar trends were derived where voice commands were used more than touch and gaze. Behaviors emerged such as participants would focus on their area of work when iterating to the next step, and participants would focus on the step instructions when going to the previous step. From the beadwork ranking analysis, we reached a discrete set of rankings between two experts, however there were no statistically significant differences between the beadwork quality and measure of work done across the learning conditions and their associated stitches. Through the interview analysis, I derived how participants felt about different aspects of EmbodiAR and the learning conditions.

Chapter 7

Discussion

7.1 Introduction

As I have derived the results from my study, I now discuss the implications of the results on my research questions and design decisions based from prior work. I also discuss current work from the Gesture and Form project using EmbodiAR and future directions from the implications generated here.

7.2 Implications of Results

7.2.1 Comparison between AR learning materials and Videos and Figures

With the comparison of the AR learning conditions and Video and Figures, the results indicated similar helpfulness notably due to the lack of statistically significant differences. The lack of statistically significant differences was observed across how participants felt about the learning materials (NASA-TLX, SUS scores), how they interacted with the conditions (proportions of interaction techniques and learning materials looked at), and how they performed (beadwork quality and measure of work done). Additionally, when prompted which condition participants preferred in the interviews, there was a similar distribution of preference across conditions. Thus, the visualized hands and dynamic 3D bead model found similar results to that of videos and figures. However, there were numerous instances where participants preferred different aspects from each of condition.

Within the learning materials there is statistically significant differences between the rated helpfulness of the 3D virtual hands in comparison to the other learning materials. This aligns with the results from the interviews where participants most commonly reported the virtual hands as unhelpful since it was lacking crucial context of the beadwork within the visualization. In addition, participants were able to derive their own hand movements required from the 3D bead model. This is in contrast to the design of the learning materials where the hand movements were intended to be derived from the virtual hands and not the bead model. This does however fall in line with Fong et al. [11] where participants could derive the hand movements required from the visualization indicating where to proceed with the task without showing indication of hand movements. Thus, within the AR conditions, the 3D bead model was much more helpful than the 3D virtual hands. This implies that the context provided in the 3D bead model (i.e., bead form) is more helpful than the context provided in the 3D virtual hands (i.e., gestures of hand movements).

The 3D virtual hands addressed the shortcomings described by Edlin et al. [20] for rendering virtual hands by utilizing their suggestion to more accurately depict the recorded virtual hands. This was addressed by utilizing a skinned mesh render of a complete hand model as suggested by Xiao et al. [85] instead of an abstract representation of cubes for joints and line renderers for connections. However, I found similar results as Edlin et al. [20] where the 3D virtual hands lacked helpfulness as it also lacked context of the beadwork. While a connection between the model and 3D hands were explored (i.e., purple trail and bead sliding) this relationship was insufficient for connecting the contexts, and that these auxiliary visualizations were not useful on the 3D hands. Even with more realistic representations of the virtual hands, there is ambiguity in relation to the beadwork which prevents it from being a useful representation for conveying bead weaving knowledge.

The 3D bead model resembled the bead structure representation of the 2D figure and provided additional insights. These included an improved perspective on the beads, which when rotated in space allowed for different perspectives to aid in problem solving. This aligns with results from Yamaguchi et al. [86] who found the animations and free viewpoint reduced a user's cognitive load. The 3D bead model also successfully captured elements on how to complete the actions with the sliding beads for the stringing steps, and the purple line indicator for the threading steps. The figure and video were also found to be used for problem solving.

The 3D bead model still lacked some elements of context that were helpful from the video. The video provided a realistic view of the beads, which gave participants more confidence when their beadwork matched the depicted beadwork. However, participants also found the idealistic view of the 2D figure and 3D bead model to be helpful for telling where the thread is going through due to the noise in the video which led to distraction. To account for this, the 3D bead model could have two modes which alternate between idealistic view and realistic view. Such that physics could be applied for the tension of the thread and the beads so it can provide a more natural representation.

As it was found participants tended to prefer the second learning condition encountered and the first stitch encountered more difficult, it was useful to counterbalance the learning materials and stitch ordering.

7.2.2 Comparison between placement of learning materials

In comparison between the placement of learning materials between the area of work and on the side, there were no statistically significant differences regarding which is inherently better. This falls in the middle with the mixed results between Blattgerste et al. [5] and Khuong et al. [41] regarding the contrasting results for in-situ and side-by-side placements. While this result reinforces that one placement technique may not be inherently better than the other, feedback from the interview elicits insights to aspects from the different positioning approaches which could be useful.

Participants compared their work to the 3D bead model, figure, and 2D video representations. As participants used the model and figure representations for diagnosing issues, they found it easier to compare the model to the beadwork when it was close to the area of work. This was primarily described by the relative distance between the model and work (e.g., "having to look back and forth" -P5). This was also problematic between the video and work, as participants would miss what is going in the video while they were looking between the two, and instead wanted the video in front of them.

This extended beyond diagnosing issues to maintaining focus on the task as participants found having the bead model situated on their hand as useful for being able to reference quickly. However, there were other participants who found it to be cumbersome to have to it anchored to their hand as they had to tilt their wrist to view the model in their preferred perspective. This could be partly due to the pose of the model depending on the pose of the hand, but different methods of anchoring which are not dependent on the pose of the hand (e.g., fixed above hand) could be explored. Additionally, some participants preferred a fixed perspective as only one perspective (i.e., directly on the side) was found useful for viewing. In contrast, other participants found the ability to rotate the model for other perspectives useful to view the path of the thread in the model.

Das et al. [15] found experts would physically place their hands over novice weaver's hands, however the helpfulness of this technique did not seem to translate into my implementation of the Embodied AR condition. This is due to participants noting in the interview how the 3D virtual hands got in the way of their work and that the movements were distracting. To overcome the issues of obstructions, I suggest detecting where the user's work is located and using eye tracking data to ensure the digital content is not interfering with the gaze to the work area. In comparison to the hands off to the side, there were no complaints regarding placement, however participants did not understand how the hands were moving in relation to its space. Thus, the results suggest there is a trade-off between placing 3D virtual hands at the area of work (useful for understanding how the hands relate to the space) and off to the side (less distracting).

7.2.3 Design Implications

Interaction Techniques

There were no significant differences in the use of voice commands, gaze to select, and touch between the different learning conditions. However, trends existed between conditions where participants used voice commands as the primary interaction technique. This aligns with the results from the interviews where participants notably preferred voice commands (potentially due to the hands free aspect as all the learning resources can be simultaneously referenced). The results aligned that touch had the lowest utility as it required participants to drop the beadwork in their hands. This suggests offering voice commands as an interaction technique for tasks which require the use and focus of the hands. Notably, 67.7% of the voice events occurred with a focus on the area of work with a similar distribution across all the three learning conditions, which implies users used voice commands while primarily having their gaze focused on their work. These findings suggest a solution to the issues with traditional interaction affordances described by Heinemann and Möller [32].

The first interaction technique (voice) proposed within the tutorial is a notable consideration, as it may had an impact on their following interactions with EmbodiAR. Thus, the tutorial was designed to teach the user about the varying options to interact to reduce the potential impact to the user's bias towards a particular interaction technique. There was no defining reason why voice was selected over touch or gaze for the first step, however there could be a relation as to why voice was used as the primary interaction technique.

Show Progression Towards an End Goal

A selection of participants inquired on a progress indicator towards an end goal. As EmbodiAR currently loops between steps as designed by traditional step-by-step figure-based instructions, there is no ending condition on when they should end their work. Confusion was elicited as they were unsure what they working towards. This is illustrated by P14, "At some places I thought OK, so how long do I have to continue and when to stop? Was it, it should so maybe the with the progress, there should be an end goal. Also show so this is how the end model should look like. So something like that so that one person can know".

Model Should Not Reset on Loops, Keep up with User Model

Another issue regarding the looping of steps is presented for the bead model (both 2D figure and 3D bead model). The bead model resets to an earlier state of the beadwork when the instructions loop, effectively creating a disconnect between the pictured model and the user's current beadwork. Participants indicated how they would have liked the model to keep up with their beadwork. This issue is illustrated by P24, "the model didn't look exactly what I was doing, so I kind of lost because the structure was different and what I was hearing was different and I had to follow the commands so that is the part where I got it got cut".

This opens a potential avenue for dynamically created learning material, as it can maintain the state of instructions with the progress of the user. While this is not explored here, it would be interesting to investigate how this desire scales with the growth of the beadwork.

Desire for Feedback on Mistakes

There were cases where participants ran into mistakes and had to troubleshoot how to rectify the situation. Some participants indicated a desire for feedback on detecting and correcting their mistakes. This is illustrated by P24, "So if there is something that can give me like an orientation of, OK, for example like I made an error and if there is a if there is something that tells me how to rectify the error, it would be really useful". This opens up for possibilities such as machine learning to assist in detecting and correcting user error. This motivation is reinforced by the findings from Büttner et al. [8] who could reliably prevent systematic error due to immediate feedback.

Utility of EmbodiAR

Across the conditions, participants were found to focus solely on the area of work as time goes on and less at other areas such as the step instructions. These outline the cases where participants have learned the step and reduce the reliance on the instructions. When participants reached proficiency with the stitch, in some cases they stopped interacting with the system altogether while working on the beadwork. When prompted during the interview about their reasoning, responses generalized to having sufficiently memorized the stitch and they no longer needed the learning materials. This could imply the learning materials were more helpful at the beginning and less as time goes on. This may suggest the system is useful for beginners when learning a new stitch, or for learning more complex stitches as the users may not be able to memorize them.

7.3 Current Work

Within the Gesture and Form project, EmbodiAR is being used as an educational resource in the context of a bead weaving workshop that is being conducted by the cultural anthropology and material culture studies section of the project. This will help in supporting the acceptability and viability of a state-of-the-art headworn AR-based application via an in-situ deployment process. Interesting findings could be drawn between the usage of the application in a lab environment as presented in this thesis, and a workshop setting. For example, the setting may impact how novice bead weavers would interact with the system (i.e, would they still opt for voice commands or opt for gaze or touch). Additionally, with the context of the workshop there are options for collaboration between other novice bead weavers and an expert instructor. How participants choose to interact with the systems and others would draw interesting findings regarding the ability for collaboration.

7.4 Future Work

The design of EmbodiAR could be capable to facilitate more forms of craft rather than only bead weaving. EmbodiAR could be expanded to cover crafts such as knitting or weaving. Additionally, it could be used beyond crafts and focus on other tasks that are common in research such as Lego assembly [28, 5, 41]. It may be useful to explore the usage of the learning resources across these different tasks to correlate the utility of the AR learning materials cross additional contexts. However, as noted in my design it is important to respect the cultural heritage which are rooted within these craft practices. The responsibility is upon the researchers who extend this work to continue respecting the boundaries of cultural heritage.

As this study controlled the traditional materials to be conveyed in AR, it lacks a comparison between the traditional mediums that videos and figures are presented (e.g, a computer monitor, or paper). While the interaction modalities provided via AR have been found to be helpful, it would be interesting to compare the usefulness of other mediums that can support similar capabilities. In addition, while the embedded audio is omitted from the video representation, including that could be explored.

While the 3D virtual hands were not useful for the context of bead weaving, the utility could be explored for teaching general hand movements. This is described by P16, “my brother is autistic, and I know it took us a while to explain to him how to hammer stuff in and this can be a great example of that”. Thus, additional research can help determine which contexts embodied hands may be a useful visualization.

As noted, results between the comparison of some learning materials is limited as they are not direct alternatives due to different levels of context available within them. While some limitations are applied to the comparison between the results (e.g., 3D bead model may be more helpful than the 2D figure either due to the 3D format or additional animations), more research can be explored to isolate these qualities between the learning materials. For example, this could explore the impact of animation between figure-based representations, or compare the helpfulness of 3D hands with embedded beadwork to videos.

As EmbodiAR focused on a subsection of the bead weaving tasks involved, the integration of additional tasks could be explored (e.g., threading a needle, extend the working thread, tying off the existing beadwork, creating a specific accessory with set goals). This additional research could be beneficial for a more general representation of what forms of craft are useful to be represented in AR.

While prior research has explored using hand tracking information to document the creation process, my findings question the utility of hand tracking information for capturing and visualizing cultural heritage. More research could be beneficial to determine how to visualize hand tracking information for the context of craft work, or how the information captured could be further processed for meaningful representation.

Chapter 8

Conclusion

In this thesis, I identified the limitations from traditional materials for learning handcraft in the context of bead weaving. I developed EmbodiAR, which compares videos and figures with new AR learning materials focused on teaching embodied knowledge for the context of beginner bead weaving stitches. Using a mixed within/between-subjects user study, I explored two research questions focusing on the comparison between the learning materials and their placements. I found the new AR learning materials had a similar helpfulness to traditional video and figures. However, the 3D virtual hands were found to lack crucial context, making them less useful than the 3D bead model. Extra measures to prevent obstruction are required when placing learning materials at the area of work. EmbodiAR and the insights regarding learning material design and placement techniques can be applied more broadly to other handcraft focuses such as knitting, weaving, and crocheting.

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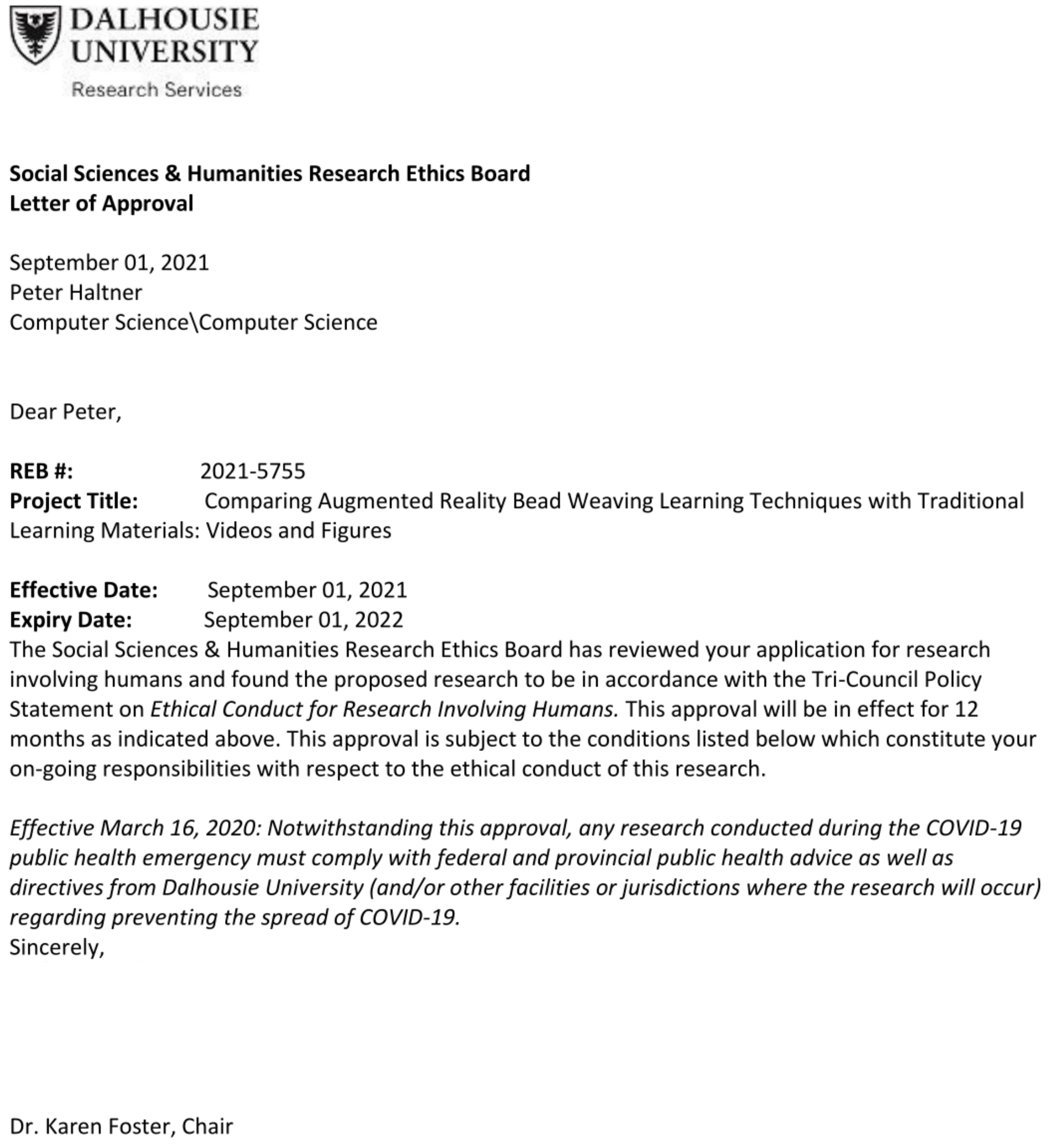
Appendix A

REB Approval Form



DALHOUSIE
UNIVERSITY
Research Services

Social Sciences & Humanities Research Ethics Board
Letter of Approval

September 01, 2021
Peter Haltner
Computer Science\Computer Science

Dear Peter,

REB #: 2021-5755
Project Title: Comparing Augmented Reality Bead Weaving Learning Techniques with Traditional Learning Materials: Videos and Figures

Effective Date: September 01, 2021
Expiry Date: September 01, 2022
The Social Sciences & Humanities Research Ethics Board has reviewed your application for research involving humans and found the proposed research to be in accordance with the Tri-Council Policy Statement on *Ethical Conduct for Research Involving Humans.* This approval will be in effect for 12 months as indicated above. This approval is subject to the conditions listed below which constitute your on-going responsibilities with respect to the ethical conduct of this research.

Effective March 16, 2020: Notwithstanding this approval, any research conducted during the COVID-19 public health emergency must comply with federal and provincial public health advice as well as directives from Dalhousie University (and/or other facilities or jurisdictions where the research will occur) regarding preventing the spread of COVID-19.
Sincerely,

Dr. Karen Foster, Chair

Appendix B

Informed Consent Form

Informed Consent for Bead Weaving Study

Project title: Comparing Augmented Reality Bead Weaving Learning Techniques with Traditional Learning Materials: Videos and Figures

Investigators: Peter Haltner, Faculty of Computer Science, Dalhousie University
Dr. Derek Reilly, Faculty of Computer Science, Dalhousie University
Rowland Goddy-Worlu, Faculty of Computer Science, Dalhousie University
Abbey Singh, Faculty of Computer Science, Dalhousie University
James Forren, Faculty of Architecture & Urban Planning, Dalhousie University
Dr. Claire Nicholas, Department of Anthropology, University of Oklahoma

Contact Person: Peter Haltner, Faculty of Computer Science, Peter.Haltner@dal.ca
REB File #: 2021-5755

Introduction
We invite you to take part in a research study being conducted by, Peter Haltner, who is a master's student at Dalhousie University. Choosing whether or not to take part in this research is entirely your choice. You can withdraw your participation at any point of the study after the consent process and not forfeit your $30 cash compensation. You may withdraw your data at any time during the experiment, where we will delete your associated recorded data. You may also withdraw your data any time prior to data analysis approximately one month after the study is completed. You can also choose to withdraw your data from use in future research outside of the research team for up until five years after the study where the de-identified data will be uploaded to a data repository. If you wish to withdraw your participation or your data, you may either tell the present researcher during the study or email Peter Haltner after the study at Peter.Haltner@dal.ca.

To be eligible to participate in the study you must have little to no experience with bead weaving, have reasonable vision and head mobility, be right-handed and be comfortable to weave using your right hand, and not have any hand/finger disabilities that make it difficult to learn bead weaving. If you are a student, there will be no impact on your studies if you decide not to participate in the research. The study is described below. You should discuss any questions you have about this study with Peter Haltner. Please ask as many questions as you like. You may benefit from this study by learning introductory bead weaving skills. An indirect benefit is the opportunity to advance research in this area and to benefit authors in experiential media.

The main purpose is to evaluate the effectiveness of different techniques to support learning bead weaving. The results of this research will inform the design of learning aids for future research.

If you decide to participate in this research, you will be asked to bead weave two small patterns using different learning materials for guidance. The experiment will take approximately 120 minutes. The equipment will be appropriately cleaned according to COVID-19 cleaning regulations and provided for you to use during the study. We will follow all other Dalhousie University and Nova Scotia COVID-19 health protocols during the experiment.

One of the investigators will have provided you with this informed consent form, which you should carefully review, and sign.

During the study, we will collect data on your experience with learning bead weaving and ask for your feedback about the bead weaving experience using an interview and questionnaires. Collected data includes video recordings and software logs captured during the bead weaving activities, audio of the interview, and questionnaire responses. All personal and identifying data will be kept confidential in publication. Anonymity of textual data will be preserved by using IDs to ensure your confidentiality. Photo and video capture will only be used in publication if consent is provided and your face will be blurred. Video data will be stored on a secure networked attached storage. People outside of the research team will not have access to the study data for the duration of the project and for 5 years after project completion. After 5 years, only the de-identified study data will be deposited in a secure digital data repository, where it might be accessed or re-analyzed by external researchers interested in similar research topics. Since part of the research team (Co-Investigator, Dr. Claire Nicholas, University of Oklahoma) resides in the United States, this means that data will be shared outside of Canada, which makes it subject to review by a third-party government (the USA).

In the event that you have any difficulties with, or wish to voice concern about, any aspect of your participation in this study, you may contact Catherine Connors, Director, Office of Research Ethics Administration at Dalhousie University’s Office of Human Research Ethics for assistance: phone: (902) 494-1462, email: Catherine.connors@dal.ca.

Project Title: Comparing Augmented Reality Bead Weaving Learning Techniques with Traditional Learning Materials: Videos and Figures

Lead Researcher: Peter Haltner, Faculty of Computer Science, Peter.Haltner@dal.ca

Participant	**Researcher**
Name: ___________________________________	Name: ___________________________________
Signature: ________________________________	Signature: ________________________________
Date: _____________________________________	*Date:* _____________________________________

The following aspects of your participation are **optional**. Please indicate your consent by **initialing** beside the item:

"I agree to let you directly quote any comments or statements made in any written reports without viewing the quotes prior to their use and I understand that the anonymity of textual data will be preserved by using IDs."

Participant: __________ ***Researcher:*** __________

"I agree to let you use photographs or video recordings during the study and I understand that the anonymity of visual data will be preserved by blurring my face."

Participant: __________ ***Researcher:*** __________

If you are interested in seeing the results of this study, please check below and provide your email address. We will contact you with publication details that describe the results.

"I would like to be notified by email when results are available via a publication."

[if this option is chosen, please include a contact email address: ______________________________]

Appendix C

Hand Tracking Visualizer: System Design

C.0.1 System Architecture

As visualized in Figure C.1, the system consists of two main parts, the hand tracking recorder and the hand tracking visualizer. The hand tracking recorder would record the user's hand states over a period of time and save that to a JSON file. The hand tracking visualizer takes in a JSON file and loads it at the start of the application. A hand visualization would appear based on the recorded data, and another hand visualization based on real-time input from the user. The system optionally analyzes the scales of the real-time hands and applies it to the recorded visualization, as detailed below. A hand tracking evaluation component computes the differences between real and expected positions of the joints; pausing the visualization if the players hands are not within a certain threshold of the correct pose. An additional indicator line controller uses the evaluation component to guide users towards the correct pose by showing lines for joints with the furthest distance from the expected pose.

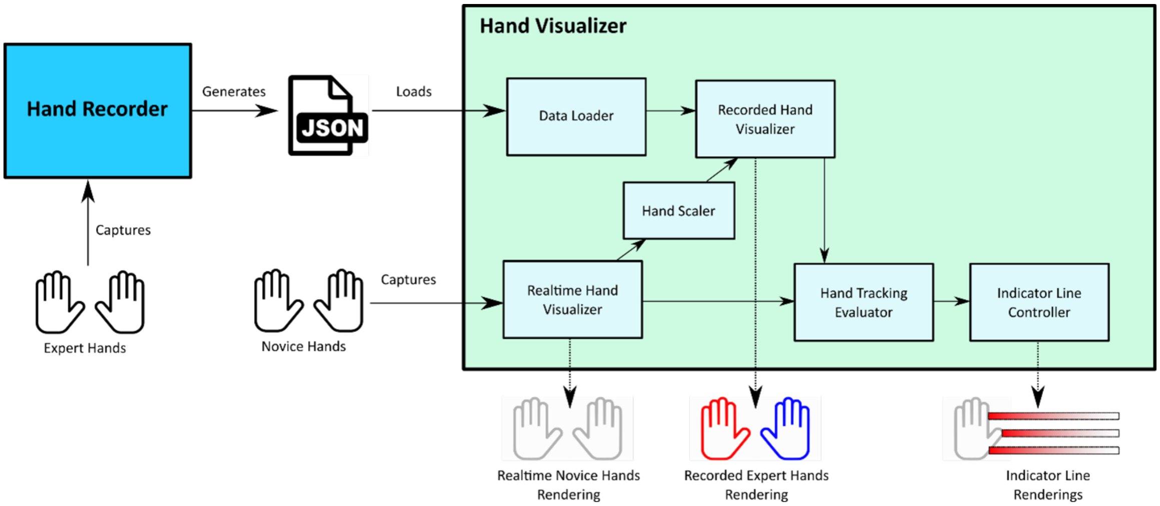


Figure C.1: Hand tracking system architecture

C.0.2 Data Loading

Data Format

The hand tracking data is saved in a JSON format as a list of hand tracking frames. Each frame contains a timestamp (relative to start of application), an offset for the right- and left-hand reference point (index finger), and two lists of joint poses (one list for each hand).

Data Processing

The system takes in a single JSON file at the beginning of the application and starts processing it into a list of hand frames. Each hand frame contains the timestamp, offsets, and joint poses.

C.0.3 Hand Visualization

Hand Visualization Rendering

The hand visualizers for both recorded and real-time hand visualizers appear very similar to the user (see Figure C.2). They both instantiate and render 1cm cubes for each joint with an associated color. For each update, the visualizers' poses are updated depending on its input source.

Recorded Hand Visualization

For each frame, the hand joint poses of the active user are retrieved via MRTK's interface. Then, the hand joints are updated accordingly from those poses. If the hand tracking is lost in one of the hands, the corresponding renders are disabled. Additionally, the tracking icon for each corresponding hand is updated to red if the hands are lost, and green if the hands are detected. The visualization of real-time hands could be distracting so it can toggle to be disabled.

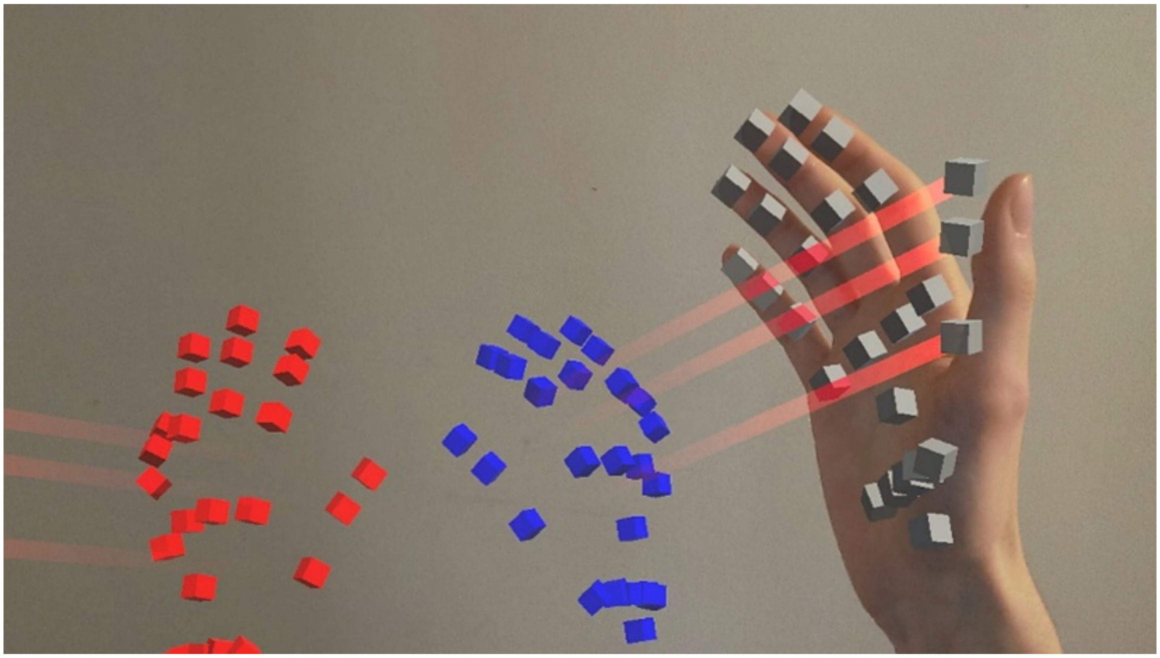


Figure C.2: Hand visualization with line renderers

C.0.4 Hand Scaling

Motivation

For hand evaluation and guidance, having the reference visualization match the shape and size of the user's hand can be important. For evaluation, if hands are different sizes, then it is harder to evaluate micro measurements for varying scales. By scaling the recorded hands to match that of the user, the reference can be more easily followed.

Algorithm

The idea is that the reference joint will not move, and then the adjoining joint will be moved to reduce/extend the distance characterized by the hand. Theoretically, the distance between the joints should be consistent throughout the playback due to the connecting bones being constant length. In a perfect capture, the distance would be consistent throughout the execution.

Toggle

As hand scaling is an optional feature, it can be toggled in the menu as shown in Figure C.3. The scaling implementation is in progress due to insufficient testing with varying hand sizes.

C.0.5 Hand Evaluation

Algorithm

The hand evaluator takes in four sets of joints (the recorded joints for both hands and real-time joints for both hands). If tracking is lost for real-time hands, the evaluation is paused until tracking is retrieved again. If tracking is lost for the recorded joint, it will skip the evaluation for that hand. As this was a proof of concept, the approach I took began with what seemed as a reasonable naive algorithm by evaluating the differences in position for each associated joint. Using the list of differing values, I summed up the lists for a left-hand sum and a right-hand sum and used the maximum sum as a measure of how closely it is being followed. Then using a threshold, it could either pause or resume the recorded visualization.

Threshold Values

The threshold for varying activities could differ, so I included a slider which would allow the user to set their tracking threshold. A very low threshold would require the joints to match very accurately that of the visualization before proceeding (as shown in Figure C.3), and a high threshold would allow the user to easily proceed without a large focus on accuracy as shown in Figure C.4. The threshold slider is color coordinated to show how acceptable a particular value is.

Visual Status Icon

Based on the recording UI, a similar icon is created which shows the status of the hand tracking evaluation. Based on the score achieved in a frame, the color represents how well they are following the sequence with regards to the slider. For example, the light is green if the user is appropriately following the recorded sequence (as shown in Figure C.5), yellow if barely meeting the threshold, and red if user is insufficiently

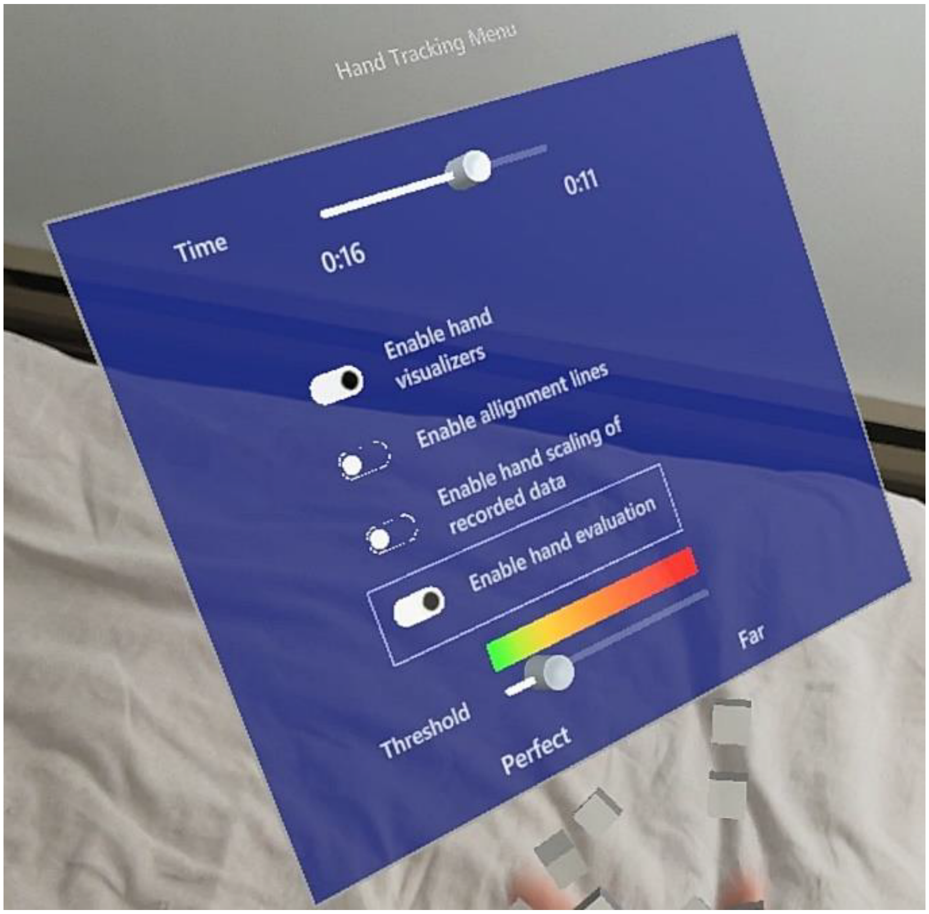


Figure C.3: Hand Tracking Visualizer menu

following the recorded sequence. The recorded visualization would be paused when the light is red.

C.0.6 Indicator Lines

Indicator lines are an additional feature which aid the user in following the recorded sequence as previously shown in Figure C.2. It builds off the joint differences from the evaluator and the hand visualizers to determine which joints are furthest from the user's hands. It renders a configurable number of lines from each hand and updates each frame to the joints with the furthest distance. The line features a transparency gradient to avoid occlusion of other joints. The indicators use object pooling to avoid unnecessary instantiations.

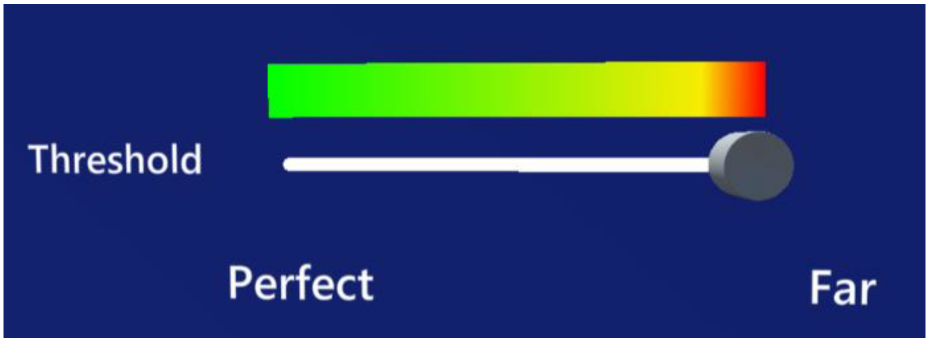


Figure C.4: Hand evaluation slider with high threshold

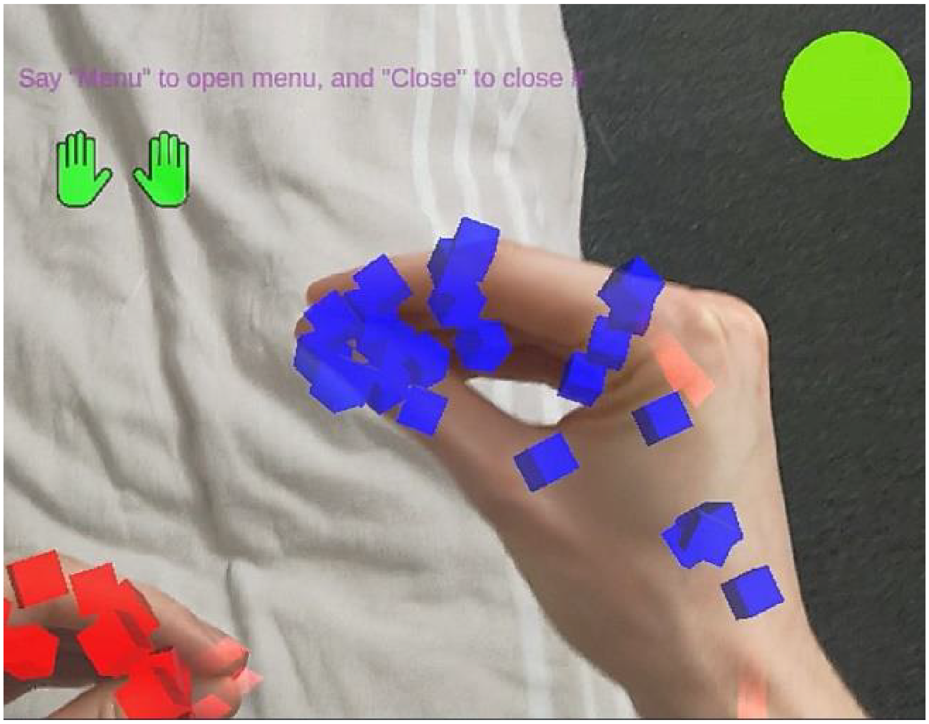

Say "Menu" to open menu, and "Close" to close it

Figure C.5: Real-time hand following recorded hands with high accuracy

Appendix D

Bead Stitch 2D Figures

D.1 Netting Stitch

D.2 Peyote Stitch

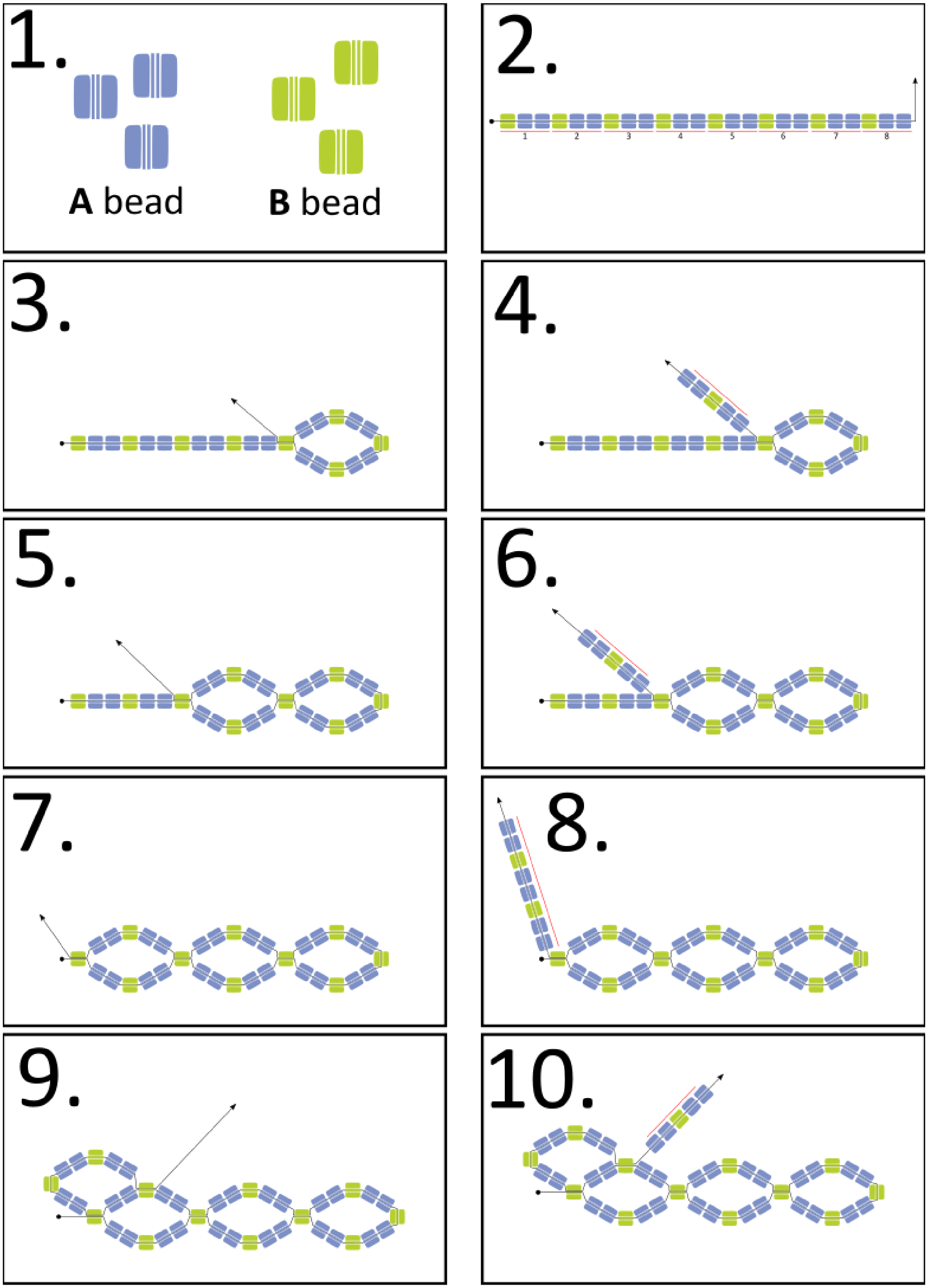


Figure D.1: Netting stitch - step 1-10

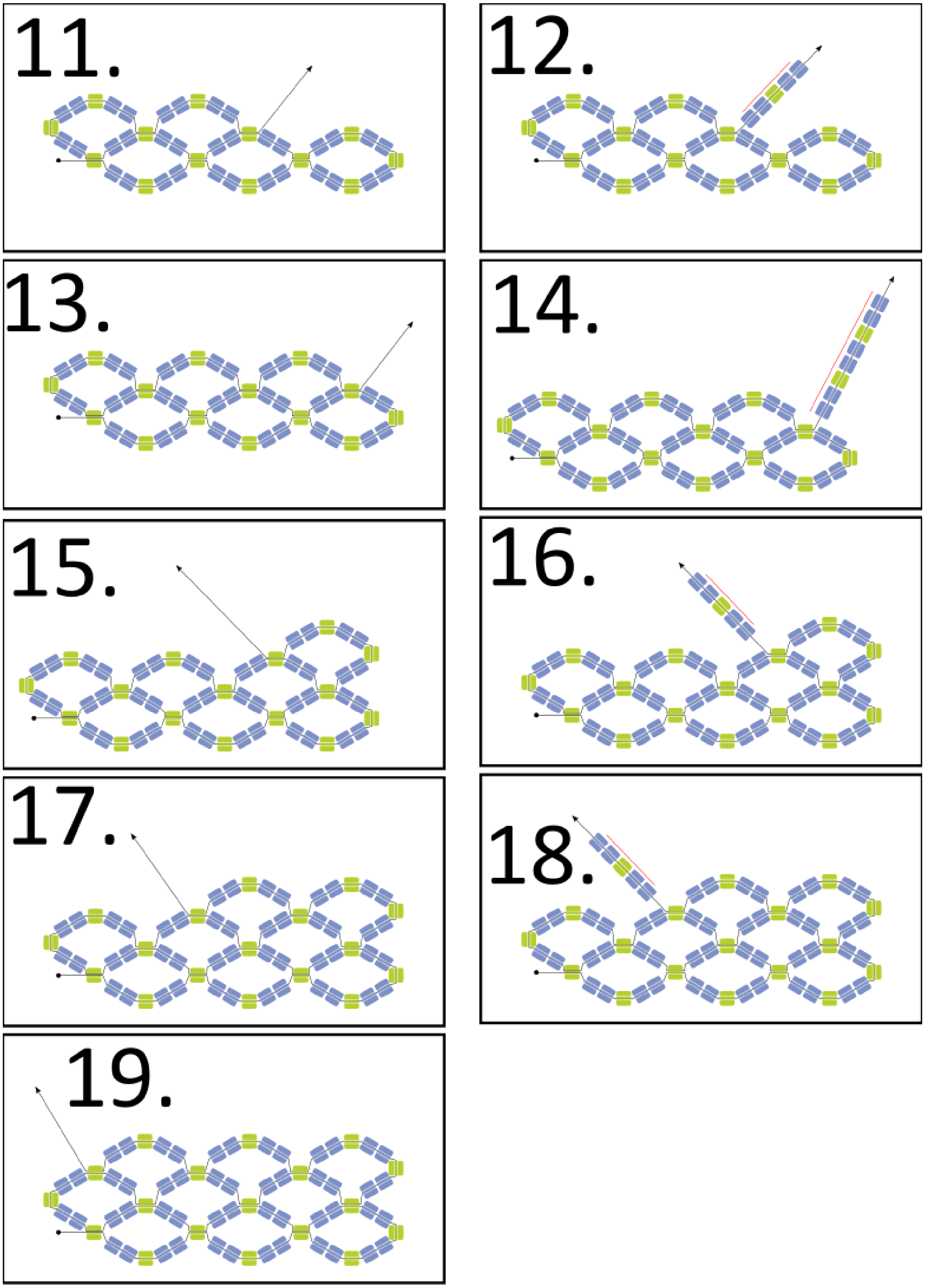


Figure D.2: Netting stitch - step 11-19

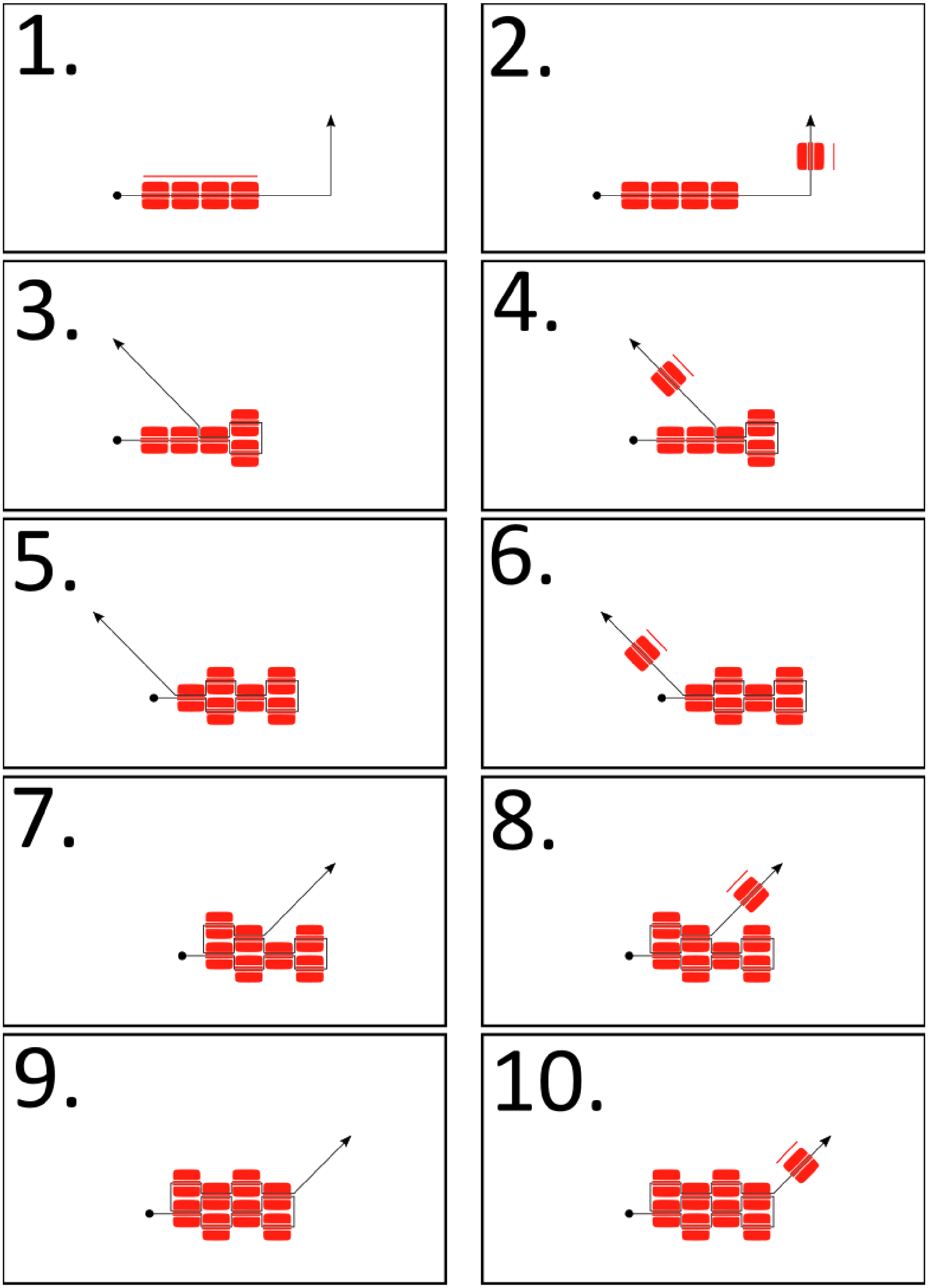


Figure D.3: Peyote stitch - step 1-10

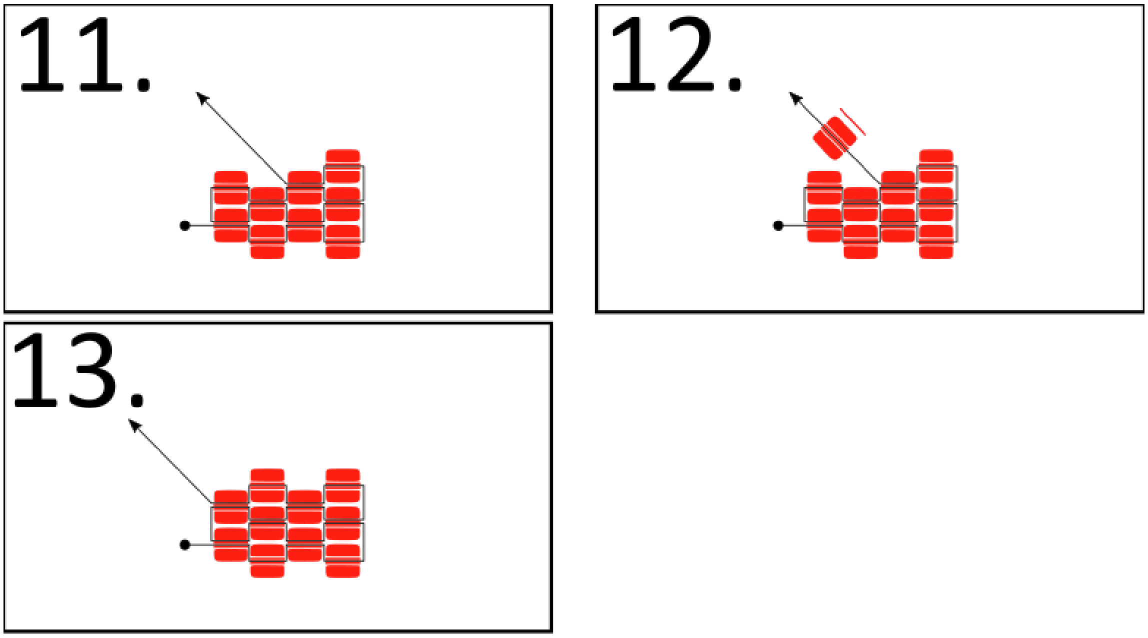
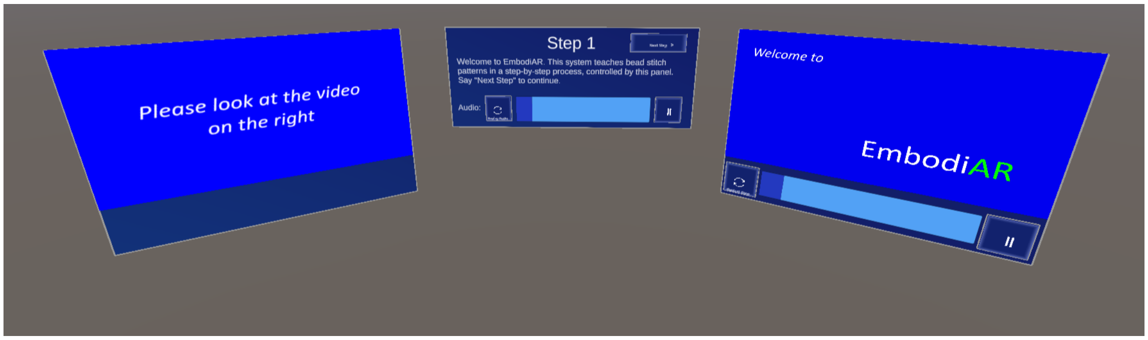


Figure D.4: Peyote stitch - step 11-13

Appendix E

EmbodiAR Tutorial



Step 1

Welcome to EmbodiAR. This system teaches bead stitch patterns in a step-by-step process, controlled by this panel. Say "Next Step" to continue.

Audio:

Figure E.1: EmbodiAR tutorial - step 1

Step 2

There are multiple ways to interact with the system. These include: Touch, Gaze, and Voice Commands

Audio:

Figure E.2: EmbodiAR tutorial - step 2

Step 3

We will now cover a few definitions required for the bead weaving process while using this system.

Figure E.3: EmbodiAR tutorial - step 3

Step 4

"String a bead": This means to add a new bead to your needle.

Figure E.4: EmbodiAR tutorial - step 4

Step 5

"Thread through a bead": This means to stick your needle through a bead already on your string.

Figure E.5: EmbodiAR tutorial - step 5

Please look at the Steps in the middle

Step 6

Once you feel comfortable navigating the interface, say the voice command "Go to Title Menu". The steps would now repeat as you move forward.

Figure E.6: EmbodiAR tutorial - step 6

Appendix F

Post-Trial Questionnaire

Post-Trial Questionnaire

Participant ID	
Learning Material	[Videos and Figures] or [Embodied AR] or [Static AR]

Please circle the relevant number for the following questions.

Evaluate the bead weaving experience in terms of the following statements:

1. I am interested in learning bead weaving.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
2. I would continue learning bead weaving using this learning material.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
3. I learned new skills for bead weaving using this learning material.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
4. The learning material was easy to follow	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses workload on five 7-point scales.

Please mark on each scale at the point that best indicates your experience of both learning and doing bead weaving using the instructional supports.

Mental Demand: How mentally demanding was the task?

Very Low **Very High**

Physical Demand: How physically demanding was the task?

Very Low **Very High**

Temporal Demand: How hurried or rushed was the pace of the task?

Very Low **Very High**

Performance: How successful were you in accomplishing what you were asked to do?

Very Low **Very High**

Effort: How hard did you have to work to accomplish your level of performance?

Very Low **Very High**

Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low **Very High**

The System Usability Scale (SUS)
Please fill out your experience with the instructional supports.

1. I think that I would like to use this system frequently.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
2. I found the system unnecessarily complex.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
3. I thought the system was easy to use.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
4. I think that I would need the support of a technical person to be able to use this system.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*

5. I found the various functions in this system were well integrated.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
6. I thought there was too much inconsistency in this system.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
7. I would imagine that most people would learn to use this system very quickly.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
8. I found the system very cumbersome to use.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
9. I felt very confident using the system.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*
10. I needed to learn a lot of things before I could get going with this system.	*1* *Strongly Disagree*	*2* *Disagree*	*3* *Neutral*	*4* *Agree*	*5* *Strongly Agree*

Appendix G

Interview Questions

Post-Experiment Interview Questions

1- Do you have a preference between learning bead weaving with the settings of the first trial or the second trial?

2- Provide 1 example (if possible) of guidance that you thought was very helpful with augmented reality. Why did you think it helpful? Do you have any other examples?

3- Provide 1 example (if possible) of guidance that you thought was not helpful with augmented reality. Why did you think it was not helpful? How could it have been improved? Do you have any other examples?

4- What are your thoughts on the following design aspects?

   a. The 3D Bead Model following the hands (if did ar_embodied)
   b. The 3D Bead Model fixed to the left (if did ar_static)
   c. The figure images fixed to the left (if did traditional)
   d. Hands placed below in front of you (if did ar_embodied)
   e. Hands fixed to the right (if did ar_static)
   f. The video fixed to the right (if did traditional)
   g. Use of red trail to highlight correspondence between hand movements and model
   h. Presence of beads and needle of hands
   i. Animation of beads being added to model.
   j. Interaction techniques (voice commands, staring to select, finger touch)

5- Did one stitch feel harder or easier to learn than the other? What felt harder/easier and why? Was it the number of steps? Was it the physical challenge? Was it the comfort of the headset?

6- Did you build any strategies when learning to bead weave? Did any of these strategies change between the different trials?

7- If you had to do another stitch, what combination of learning resources would you want to use?

8- Do you have any more questions or feedback?

Appendix H

Post-Session Questionnaire

Post-session Questionnaire

Participant ID	

1. What is your age?

a) 13 – 17 years old
b) 18 – 22 years old
c) 23 – 29 years old
d) 30 – 45 years old
e) 46 – 60 years old
f) 61+
g) Prefer not to answer

2. What gender do you identify as?

a) Male
b) Female
c) ____________________ (Short Answer Space)
d) Prefer not to answer

3. What is the highest degree or level of education you have completed?

a) Some High School
b) High School
c) Bachelor's Degree
d) Master's Degree
e) Ph.D.
f) Trade School
g) Prefer not to say
h) Other ______________________

4. Circle how often you have used augmented reality (AR) and virtual reality (VR) **before** this study.

Mobile AR (phones)	*1* *Never*	*2* *Less than once a year*	*3* *Once a year*	*4* *Once a month*	*5* *Once a week*	*6* *More than once a week*
Headworn AR (headset)	*1* *Never*	*2* *Less than once a year*	*3* *Once a year*	*4* *Once a month*	*5* *Once a week*	*6* *More than once a week*
Headworn VR (headset)	*1* *Never*	*2* *Less than once a year*	*3* *Once a year*	*4* *Once a month*	*5* *Once a week*	*6* *More than once a week*

5. Rate the helpfulness of each learning material.

Step Description (Written)	*1* *Not at all Helpful*	*2* *Slightly Helpful*	*3* *Moderately Helpful*	*4* *Very Helpful*	*5* *Extremely Helpful*	
Step Description (Audio)	*1* *Not at all Helpful*	*2* *Slightly Helpful*	*3* *Moderately Helpful*	*4* *Very Helpful*	*5* *Extremely Helpful*	
Video	*1* *Not at all Helpful*	*2* *Slightly Helpful*	*3* *Moderately Helpful*	*4* *Very Helpful*	*5* *Extremely Helpful*	*Not Included*
Figures	*1* *Not at all Helpful*	*2* *Slightly Helpful*	*3* *Moderately Helpful*	*4* *Very Helpful*	*5* *Extremely Helpful*	*Not Included*
AR Virtual Hands (Embodied)	*1* *Not at all Helpful*	*2* *Slightly Helpful*	*3* *Moderately Helpful*	*4* *Very Helpful*	*5* *Extremely Helpful*	*Not Included*
AR Virtual Hands (Fixed)	*1* *Not at all Helpful*	*2* *Slightly Helpful*	*3* *Moderately Helpful*	*4* *Very Helpful*	*5* *Extremely Helpful*	*Not Included*
AR 3D Bead Models (Embodied)	*1* *Not at all Helpful*	*2* *Slightly Helpful*	*3* *Moderately Helpful*	*4* *Very Helpful*	*5* *Extremely Helpful*	*Not Included*
AR 3D Bead Models (Fixed)	*1* *Not at all Helpful*	*2* *Slightly Helpful*	*3* *Moderately Helpful*	*4* *Very Helpful*	*5* *Extremely Helpful*	*Not Included*

Appendix I

Participant Counterbalancing Sheet

Participant Counter Balancing Sheet

Study: Comparing Augmented Reality Bead Weaving Learning Techniques with Traditional Learning Materials: Videos and Figures

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Participant ID	Trial 1		Trial 2		Verification Code
	Bead	Format	Bead	Format	
1	Netting	ar_embodied	Peyote	ar_static	P: 1 N_ARE P_ARS
2	Peyote	traditional	Netting	ar_embodied	P: 2 P_T N_ARE
3	Netting	ar_static	Peyote	traditional	P: 3 N_ARE P_T
4	Peyote	ar_embodied	Netting	traditional	P: 4 P_ARE N_T
5	Netting	traditional	Peyote	ar_static	P: 5 N_T P_ARS
6	Peyote	ar_static	Netting	ar_embodied	P: 6 P_ARS N_ARE
7	Peyote	ar_embodied	Netting	ar_static	P: 7 P_ARE N_ARS
8	Netting	traditional	Peyote	ar_embodied	P: 8 N_T P_ARE
9	Peyote	ar_static	Netting	traditional	P: 9 P_ARS N_T
10	Netting	ar_embodied	Peyote	traditional	P: 10 N_ARE P_T
11	Peyote	traditional	Netting	ar_static	P: 11 P_T N_ARS
12	Netting	ar_static	Peyote	ar_embodied	P: 12 N_ARS P_ARE
13	Netting	ar_embodied	Peyote	ar_static	P: 13 N_ARE P_ARS
14	Peyote	traditional	Netting	ar_embodied	P: 14 P_T N_ARE
15	Netting	ar_static	Peyote	traditional	P: 15 N_ARS P_T
16	Peyote	ar_embodied	Netting	traditional	P: 16 P_ARE N_T
17	Netting	traditional	Peyote	ar_static	P: 17 N_T P_ARS
18	Peyote	ar_static	Netting	ar_embodied	P: 18 P_ARS N_ARE
19	Peyote	ar_embodied	Netting	ar_static	P: 19 P_ARE N_ARS
20	Netting	traditional	Peyote	ar_embodied	P: 20 N_T P_ARE
21	Peyote	ar_static	Netting	traditional	P: 21 P_ARS N_T
22	Netting	ar_embodied	Peyote	traditional	P: 22 N_ARE P_T
23	Peyote	traditional	Netting	ar_static	P: 23 P_T N_ARS
24	Netting	ar_static	Peyote	ar_embodied	P: 24 N_ARS P_ARE
25	Netting	ar_embodied	Peyote	ar_static	P: 25 N_ARE P_ARS
26	Peyote	traditional	Netting	ar_embodied	P: 26 P_T N_ARE
27	Netting	ar_static	Peyote	traditional	P: 27 N_ARS P_T
28	Peyote	ar_embodied	Netting	traditional	P: 28 P_ARE N_T
29	Netting	traditional	Peyote	ar_static	P: 29 N_T P_ARS
30	Peyote	ar_static	Netting	ar_embodied	P: 30 P_ARS N_ARE

Appendix J

Keyword Cheat Sheet

Keyword Cheat Sheet

“Pause”

“Play”

“Reset”

“Next Step”

“Previous Step”

For researcher prompted use **ONLY**:

“Load first trial”

“Stop trial now”

“Load second trial”

Appendix K

Netting Stitch Beadwork

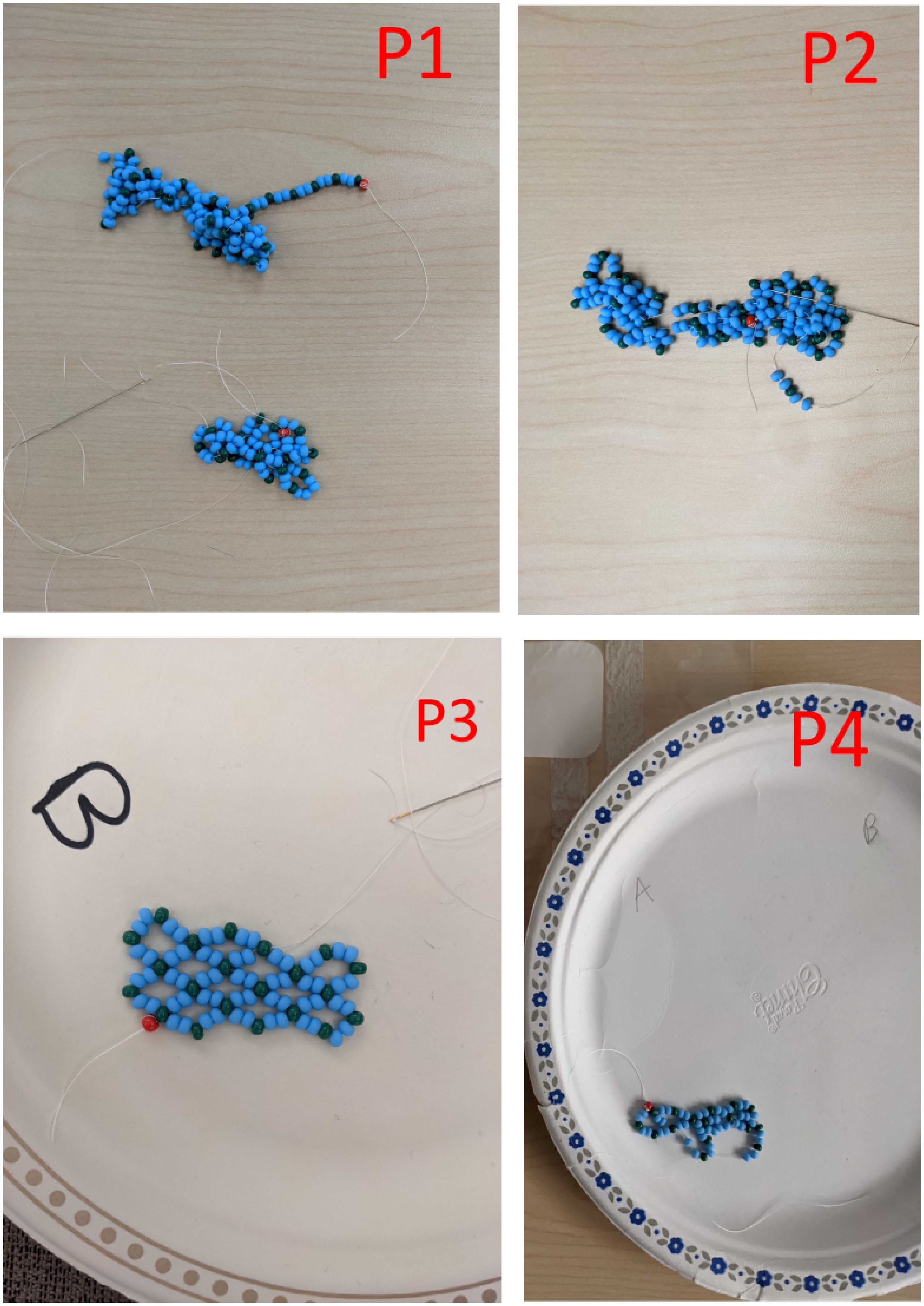

Figure K.1: Netting stitch result P1-P4

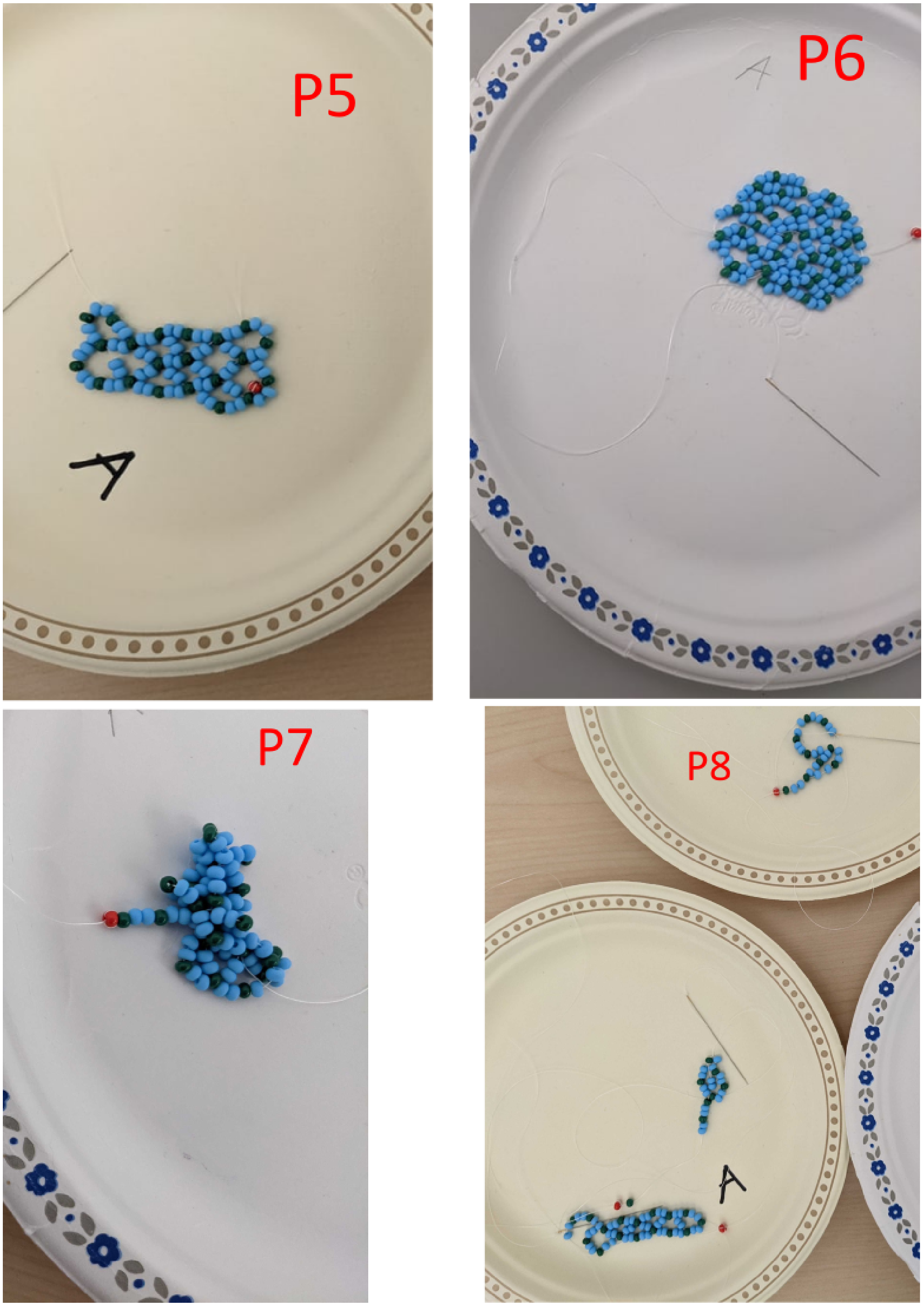

Figure K.2: Netting stitch result P5-P8

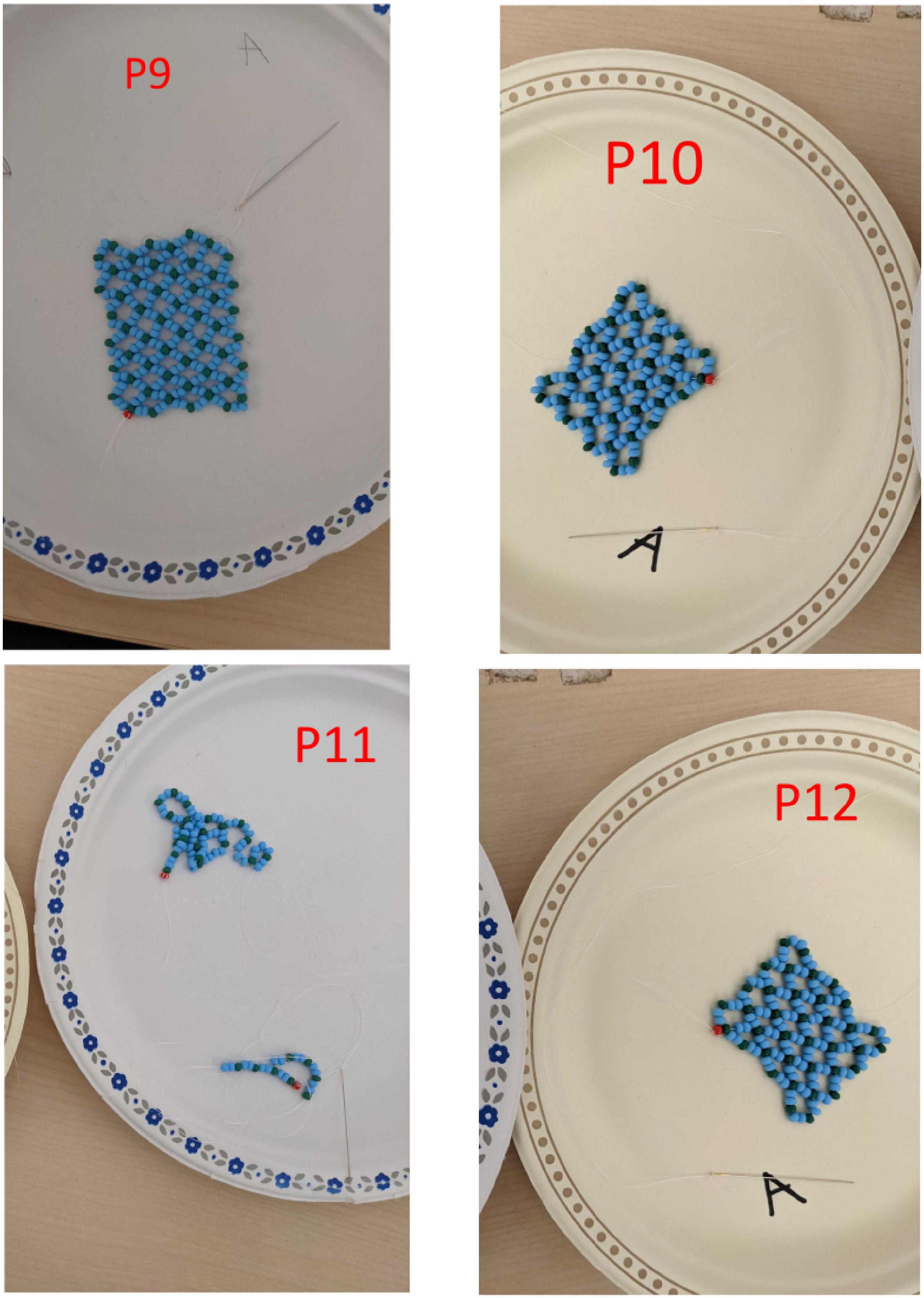

Figure K.3: Netting stitch result P9-P12

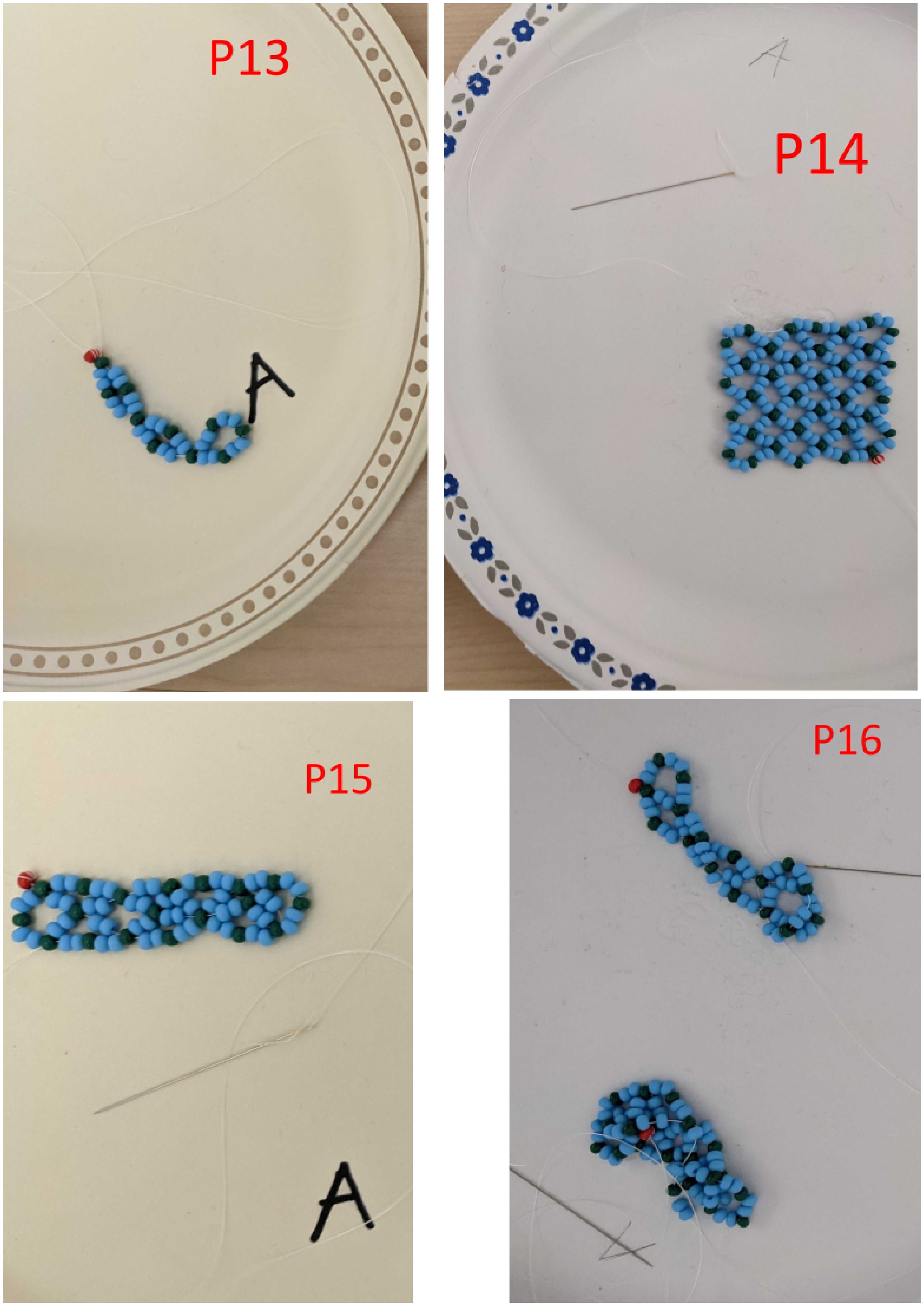

Figure K.4: Netting stitch result P13-P16

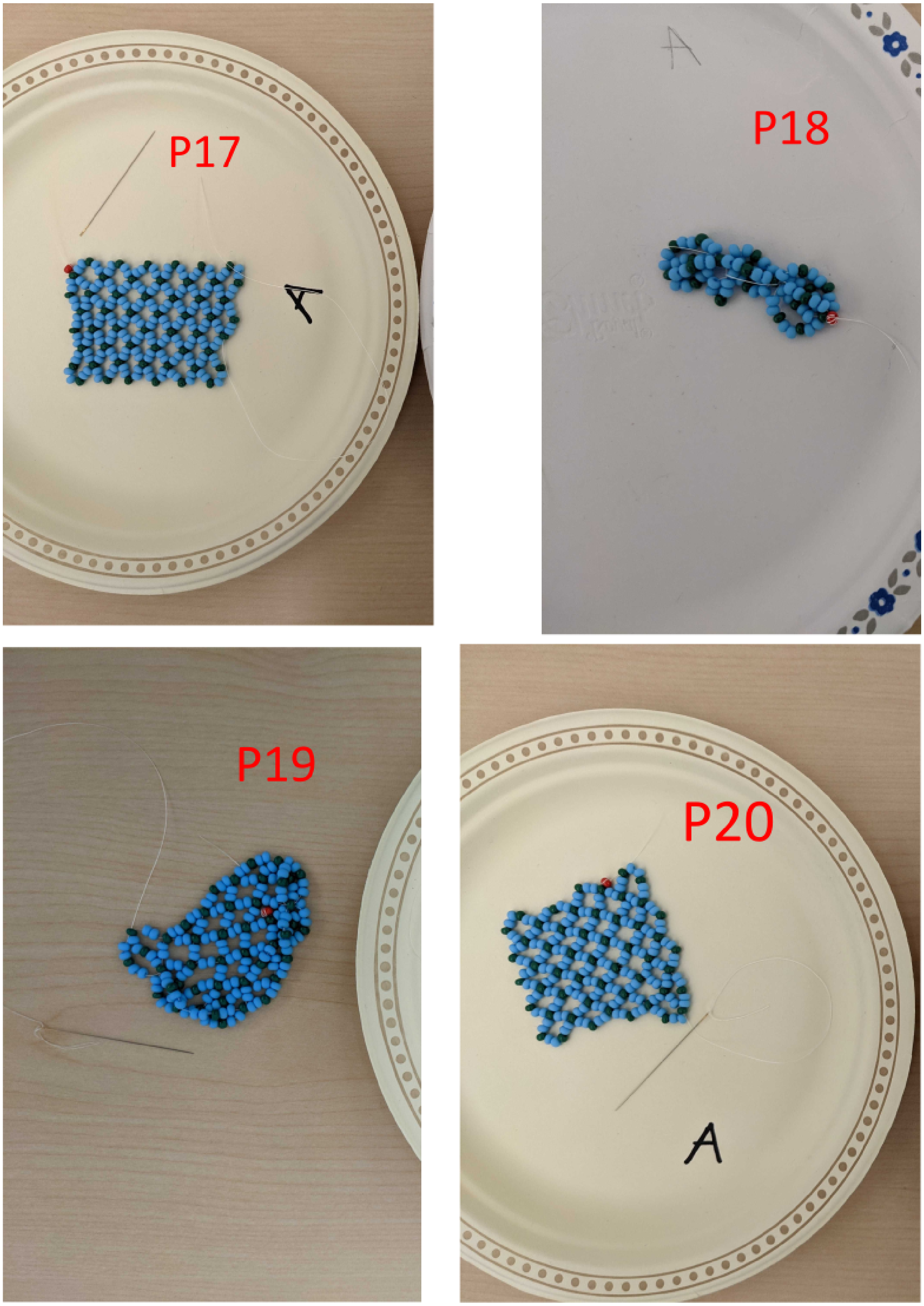

Figure K.5: Netting stitch result P17-P20

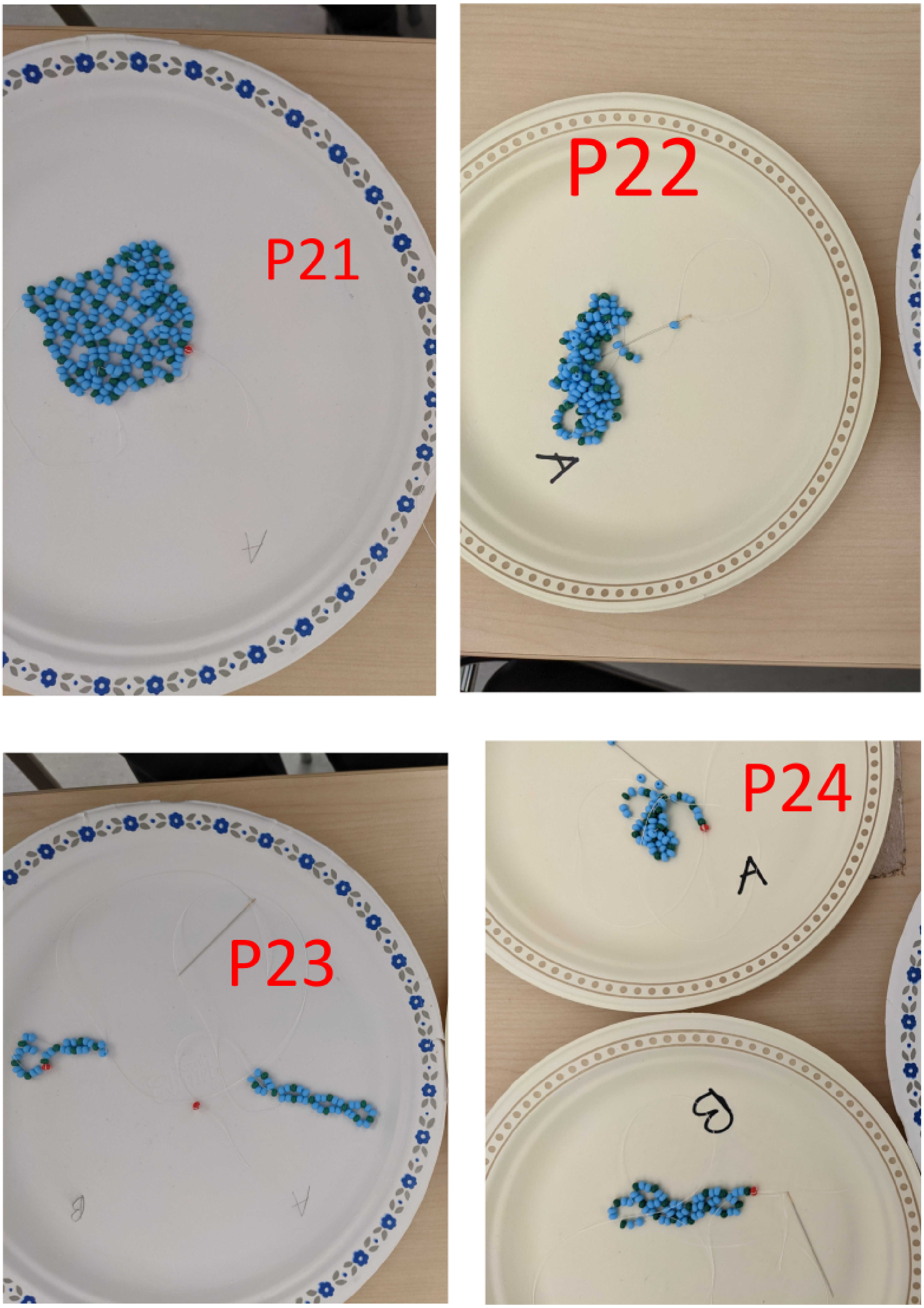

Figure K.6: Netting stitch result P21-P24

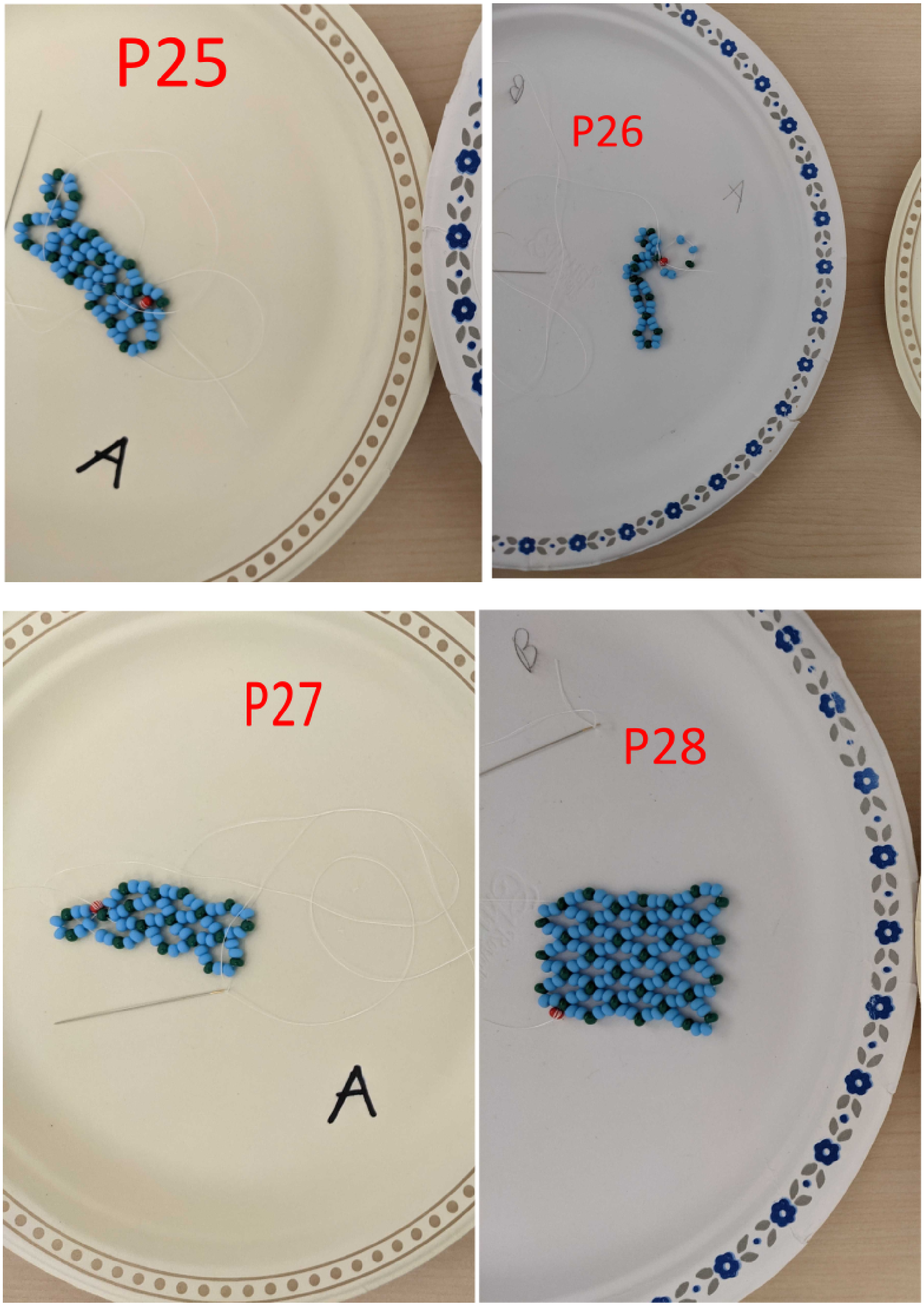

Figure K.7: Netting stitch result P25-P28

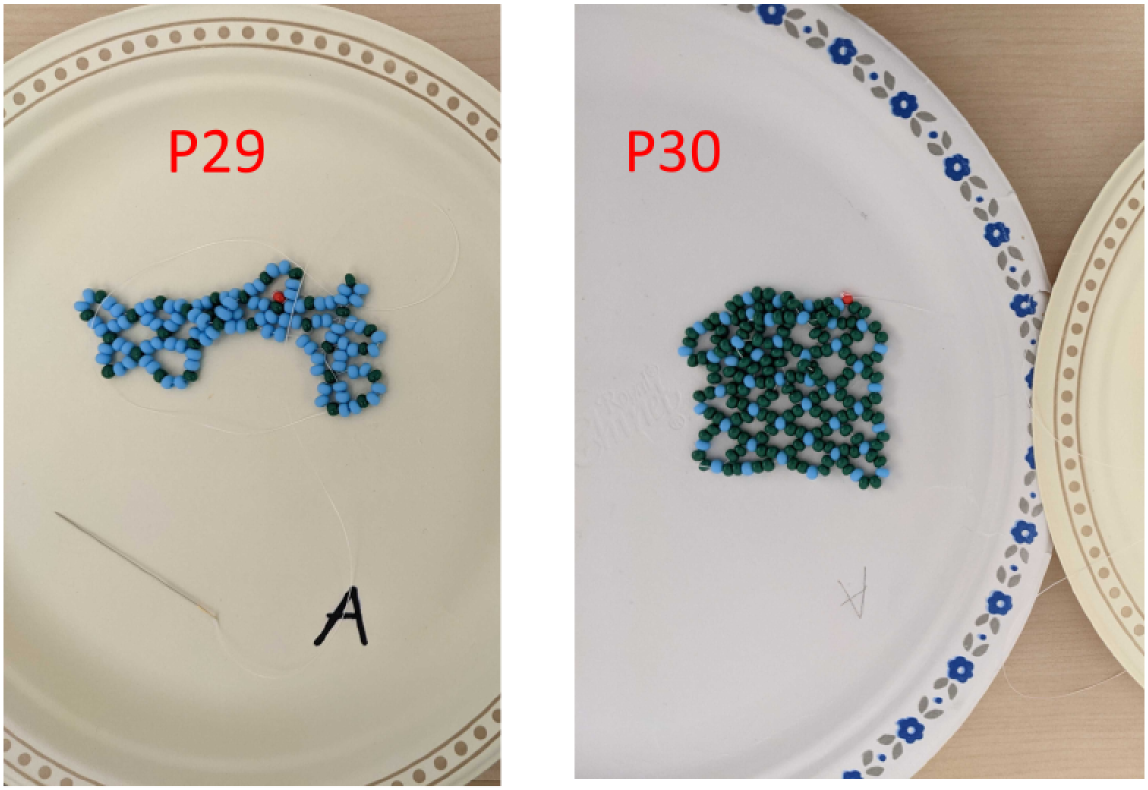

Figure K.8: Netting stitch result P29-P30

Appendix L

Peyote Stitch Beadwork

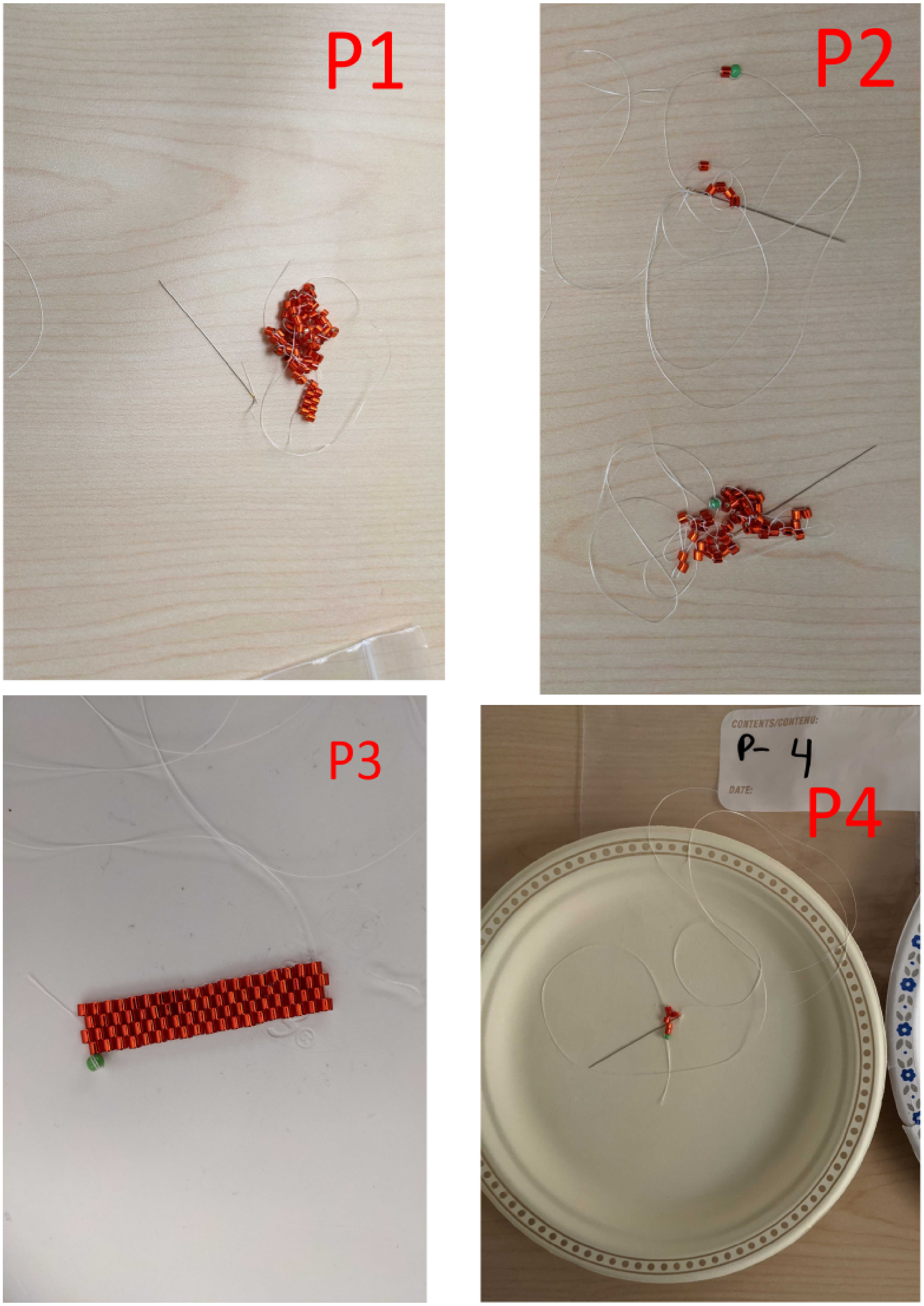

Figure L.1: Peyote stitch result P1-P4

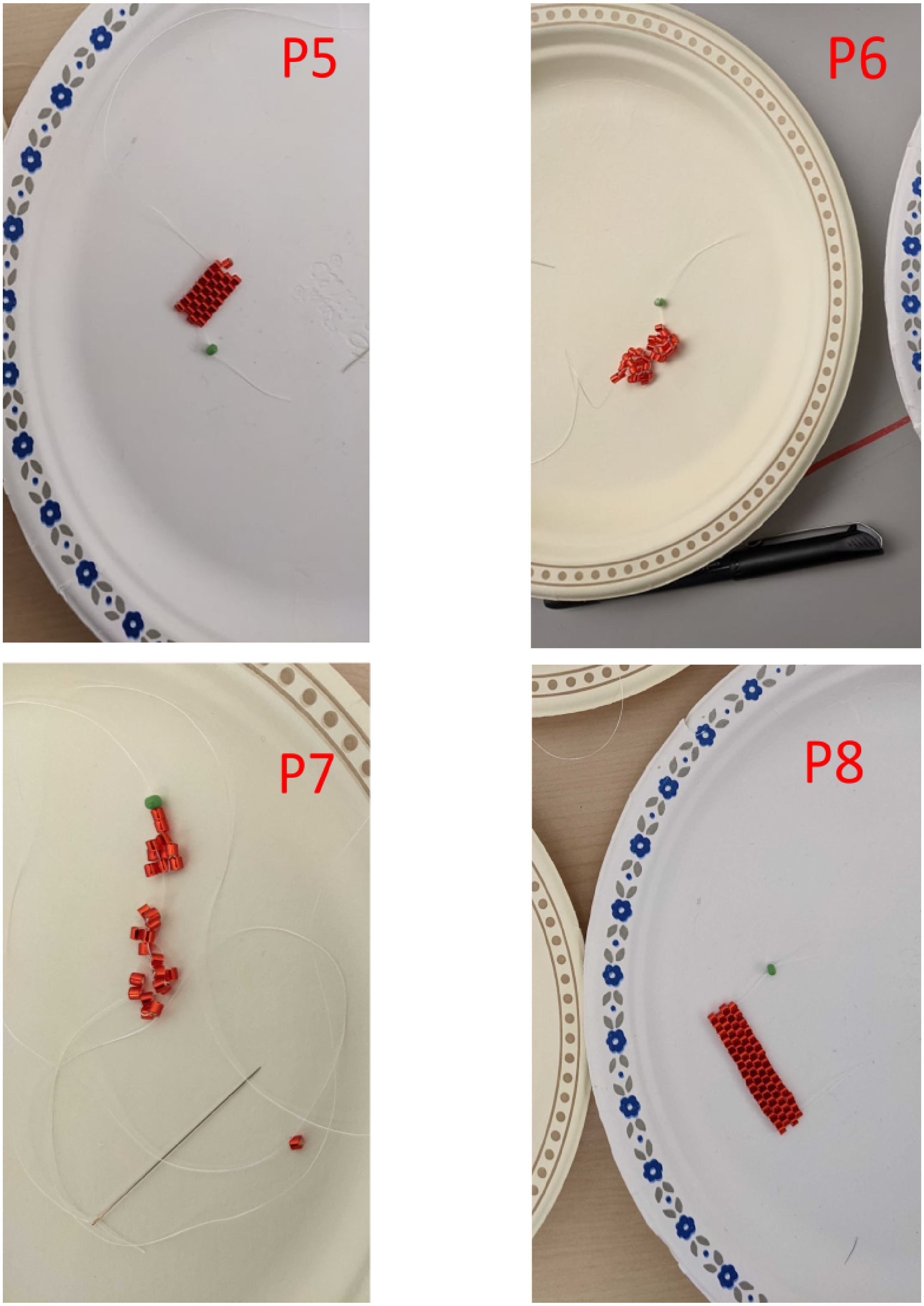

Figure L.2: Peyote stitch result P5-P8

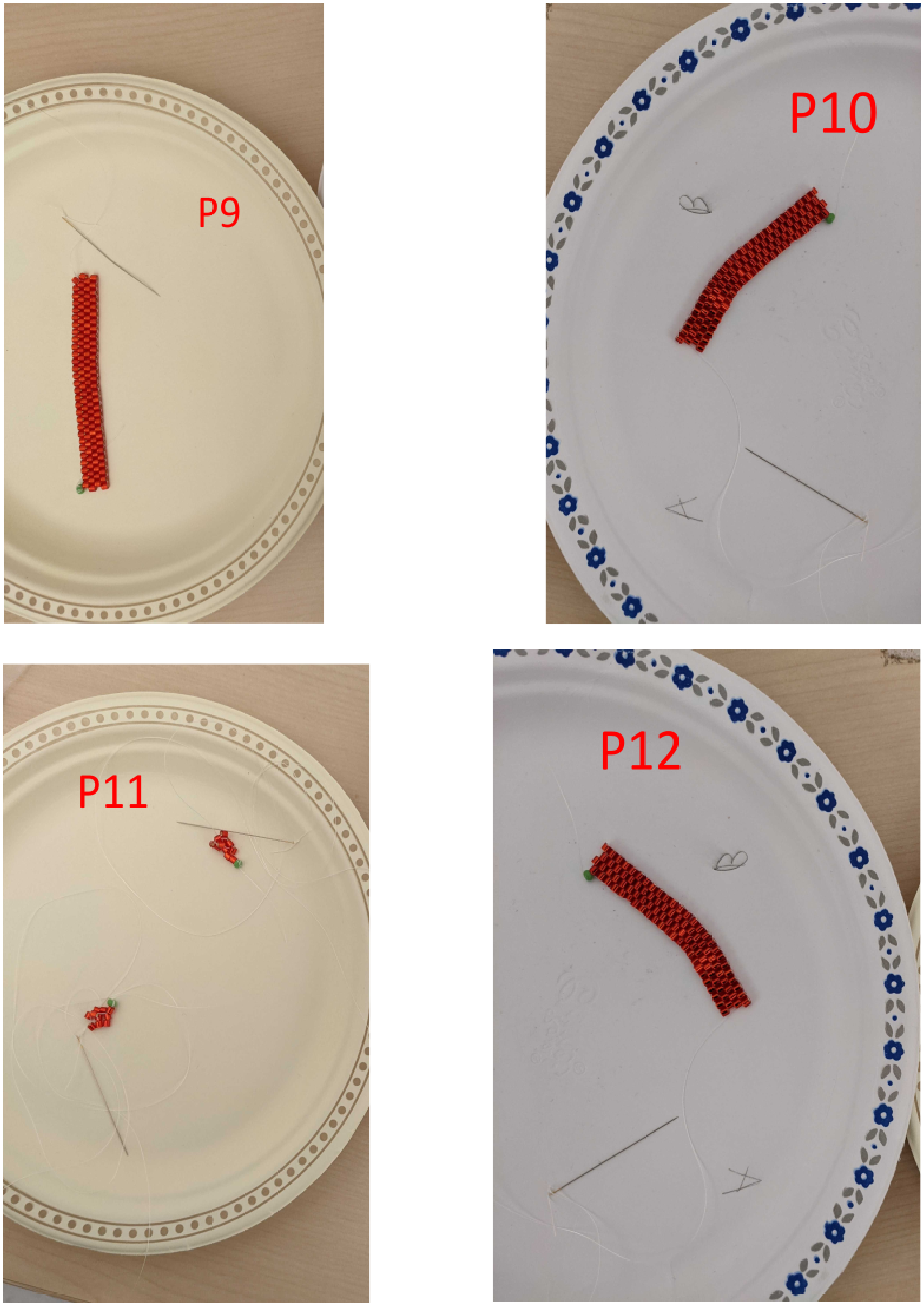

Figure L.3: Peyote stitch result P9-P12

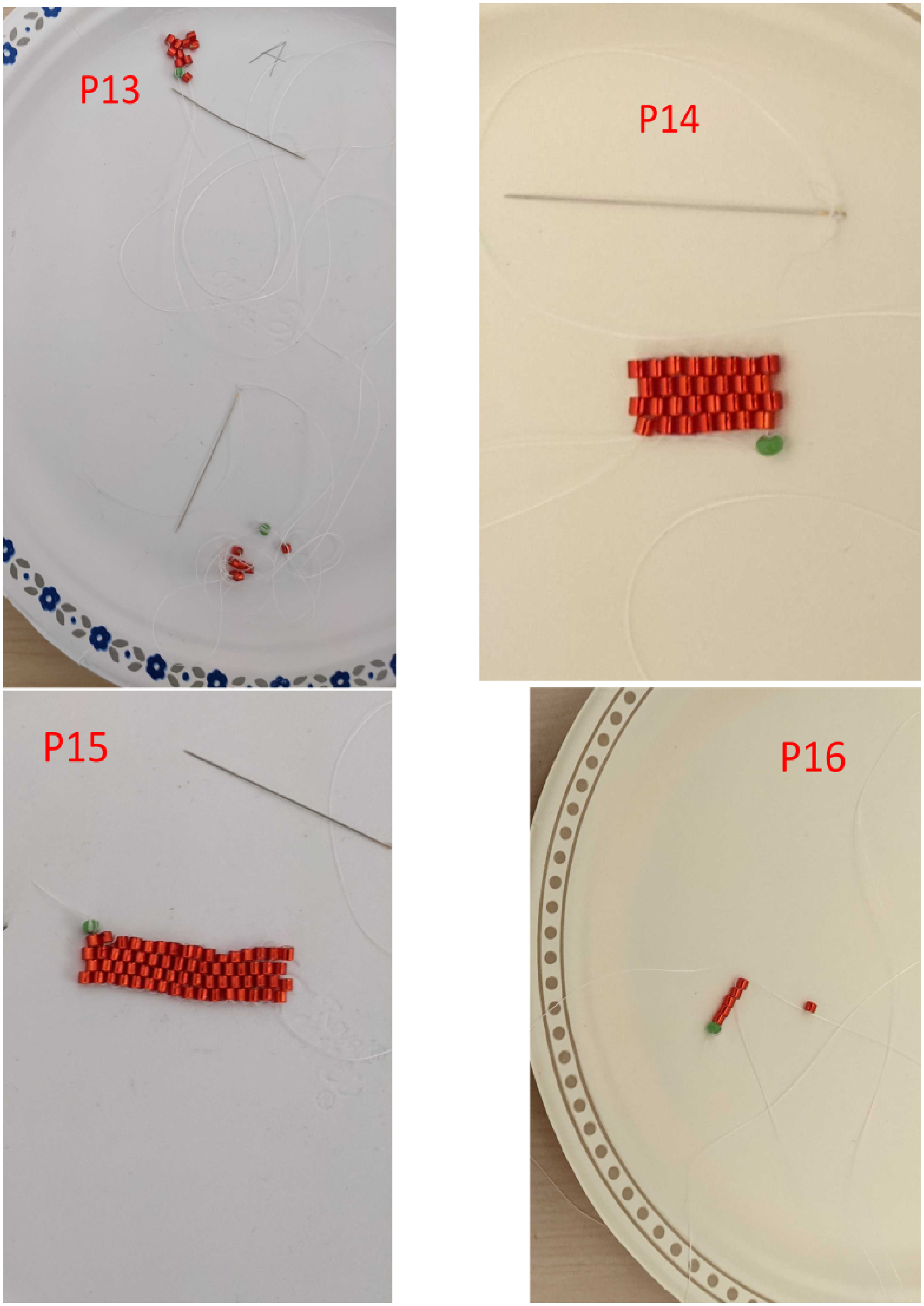

Figure L.4: Peyote stitch result P13-P16

Figure L.5: Peyote stitch result P17-P20

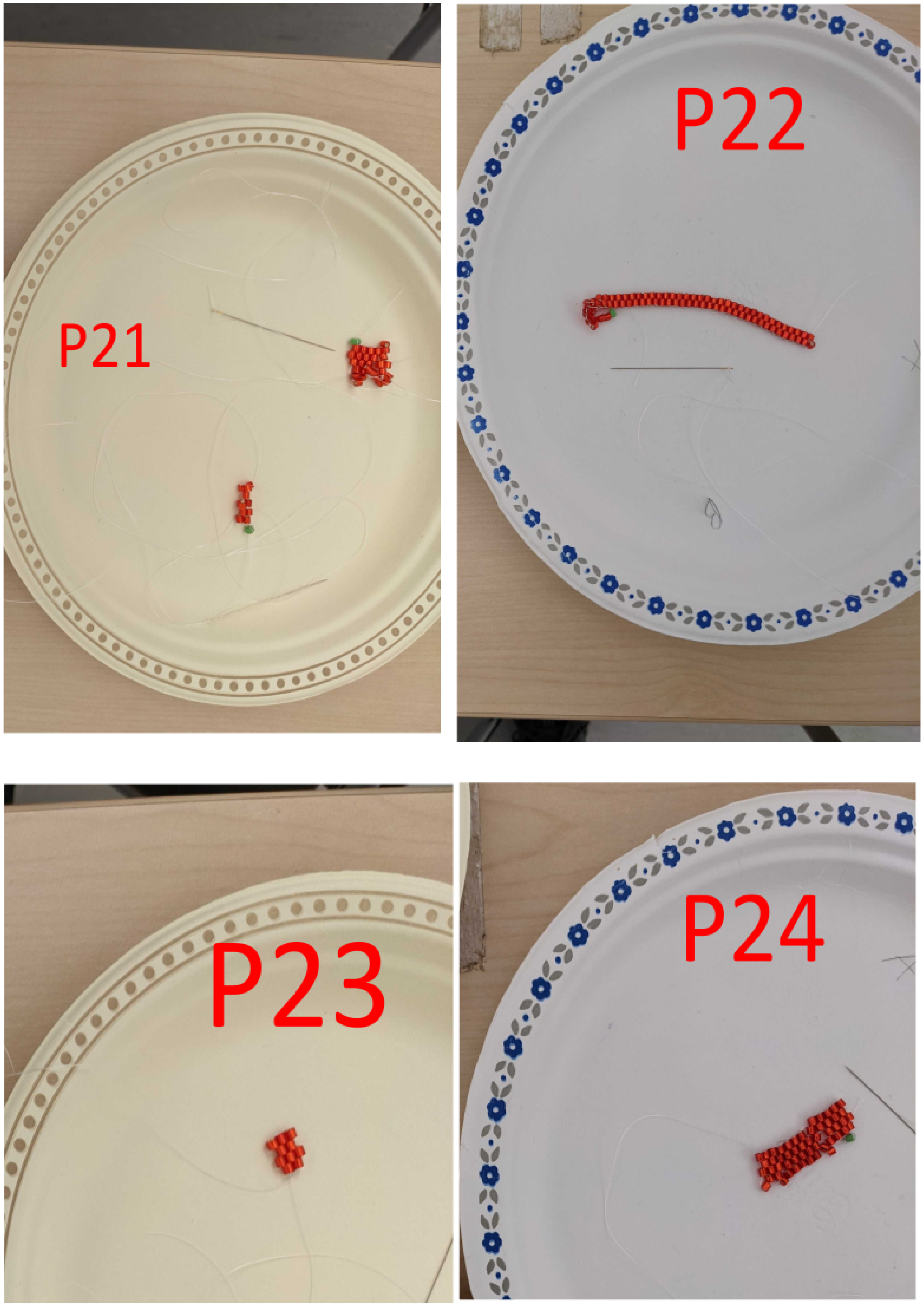

Figure L.6: Peyote stitch result P21-P24

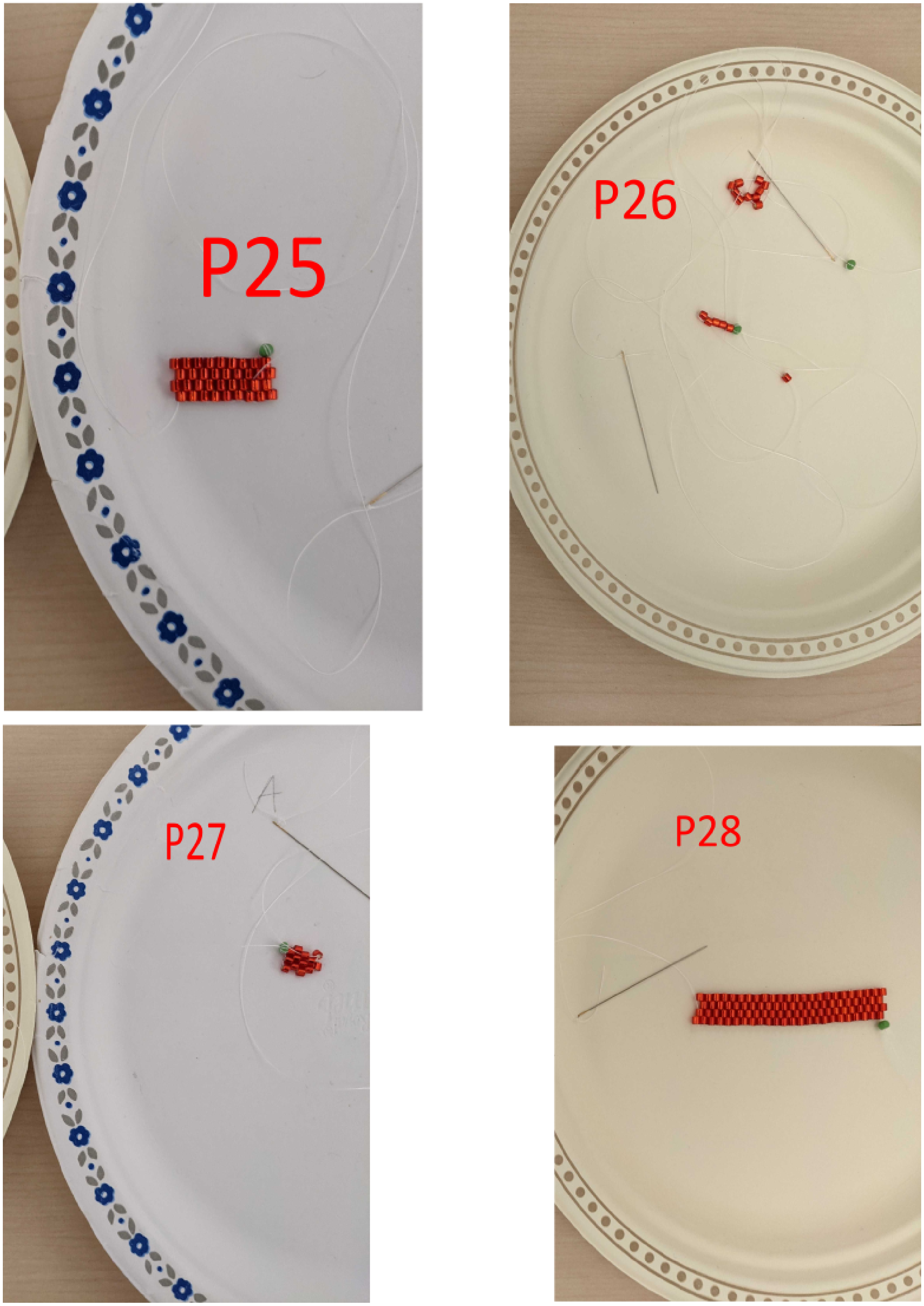

Figure L.7: Peyote stitch result P25-P28

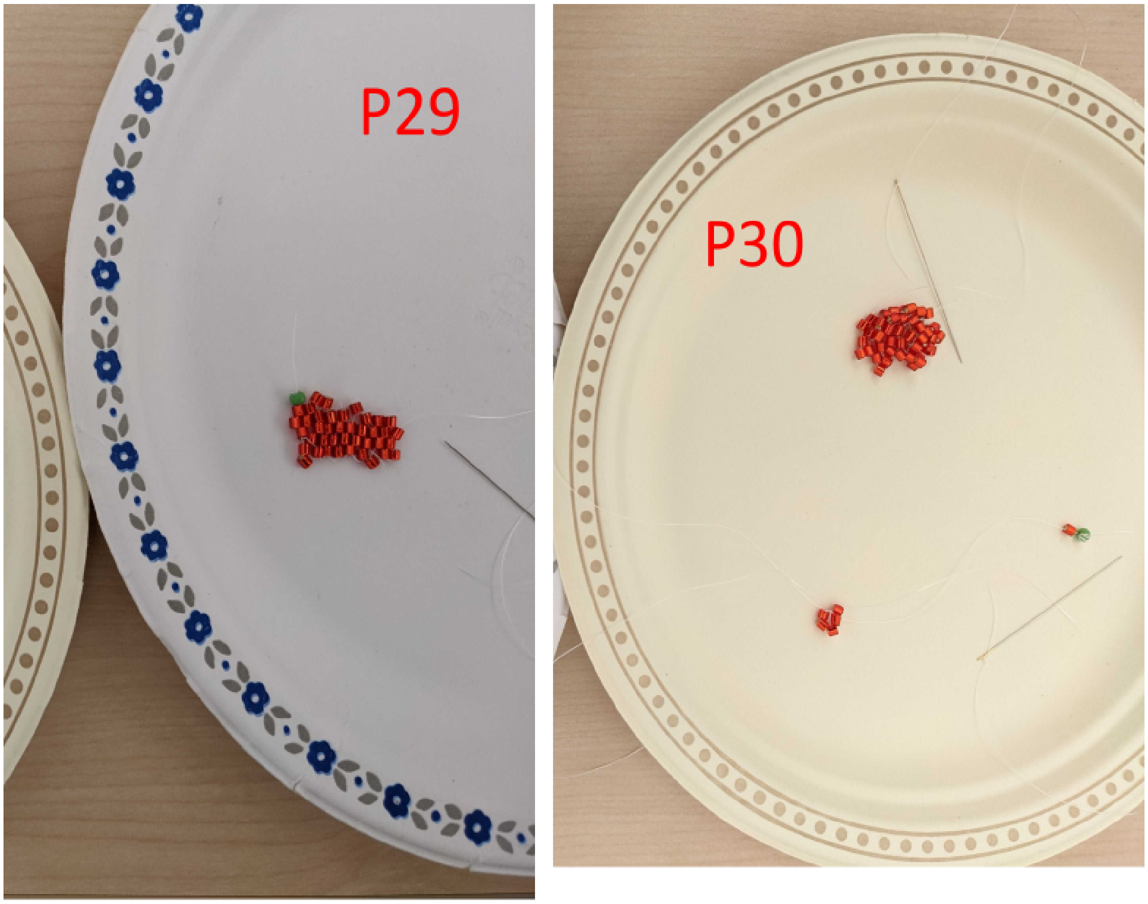

Figure L.8: Peyote stitch result P29-P30

Appendix M

Auxiliary Results

M.1 Learning Material Helpfulness Pairwise Tests

Table M.1 illustrates the results of each pair compared using the Kruskal-Wallis test. The pair order is as follows: textual description, audio description, video, embodied 3D hands, fixed 3D hands, 2D figure, embodied 3D hands, and fixed 3D hands.

M.2 Weighted Sequence Diagrams

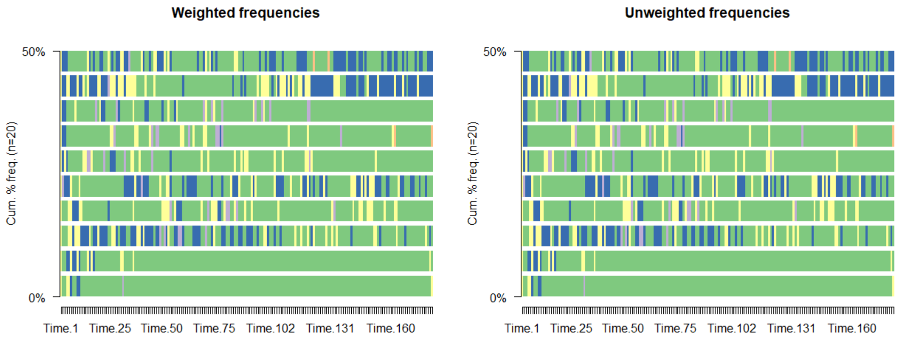

Figure M.1: Weighted sequence diagram: Videos and Figures

M.3 Interaction Technique Distribution Analysis

First, I aggregate all interaction technique events across all trials. There are 3671 total interaction events where 54.24% are voice commands (1991/3671), 26.53% are gaze inputs (974/3671) and 19.2% are touch inputs (706/3671). From the distribution of number of events across the trials: the min=14, max=178, M=61.18, median=56.5, mode=43, and SD=33.59. While voice commands have a majority, the raw interaction event count is unrepresentative across trials due to the large range and high standard deviation (e.g., the max (178) trial is equivalent to the first 9 trials (sum=188)).

Table M.1: Pairwise test results

Pair	**Chi squared**	**p-value**
x1-x2	1.3591	0.2437
x1-x3	0.5449	0.4604
x1-x4	6.9774	0.008255
x1-x5	12.8037	0.0003459
x1-x6	2.1612	0.1415
x1-x7	4.6673	0.03074
x1-x8	4.882	0.02714
x2-x3	0.08384	0.7722
x2-x4	10.8876	0.0009681
x2-x5	17.8296	0.00002416
x2-x6	0.1831	0.6687
x2-x7	1.2537	0.2628
x2-x8	1.539	0.2148
x3-x4	7.8728	0.005018
x3-x5	13.1924	0.0002811
x3-x6	0.3767	0.5394
x3-x7	1.5779	0.2091
x3-x8	1.825	0.1767
x4-x5	0.2834	0.5945
x4-x6	9.8208	0.001725
x4-x7	13.1469	0.000288
x4-x8	12.8667	0.0003345
x5-x6	15.9345	0.00006557
x5-x7	19.9452	0.000007969
x5-x8	18.8346	0.00001426
x6-x7	0.4334	0.5103
x6-x8	0.8894	0.3456
x7-x8	0.06244	0.8027

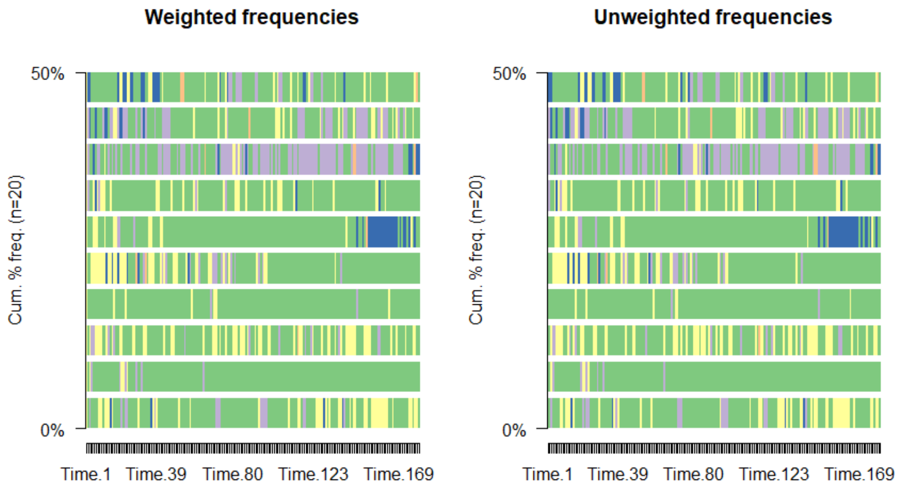

Figure M.2: Weighted sequence diagram: Static AR

M.4 Auxiliary Interview Results

M.4.1 Interaction Techniques

Participants preferred interacting with the system by voice commands (21/30 participants), then gaze (8/30 participants), then lastly touch (1/30 participants).

The benefits of voice commands were noted as follows:

- Being able to focus their attention on the beads while they work. Not needing to drop the beadwork or avert their focus, as illustrated by P11, "since my hands were engaged, I prefer using my voice command".

- Being able to cohesively progress through the steps, as illustrated by P20, "if I'm still looking, sometimes I would be still putting stuff on sort of or still like working with it and then I could just like say it and keep going like while I was still doing things so it was easier to keep looking and keep knowing what my next step is sort of in my head and then ask it to change".

- Some participants were used to the interaction via interacting with smart home devices.

- Quickest interaction.

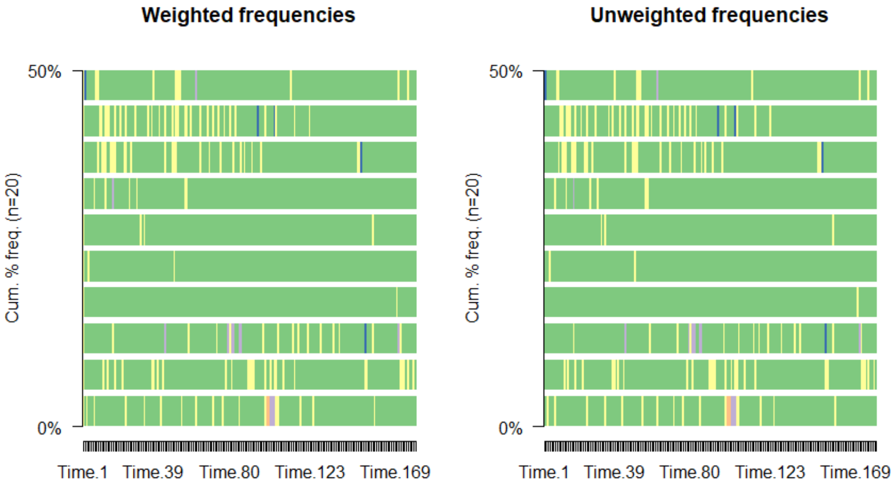

Figure M.3: Weighted sequence diagram: Embodied AR

However, some participants who had concerns with the voice commands stated the reasons:

- Voice was cumbersome for repetitive use.
- Could be difficult to remember.
- In a noisy environment, they would rather not use their voice to interact. This is illustrated by P18, "I could see depending on the environment I'm in where I'm doing it, I might prefer to just look if I don't want to be noisier if I don't want to be too loud or anything and speak out loud".
- Limitations of voice recognition software as stated by P12, "since our accent is different, it will not be able to understand sometimes".

The benefits of gaze were noted as follows:

- The same reasons as the voice commands for not having to drop their beads and needle while they are working.
- The consistent use of the same interaction, as they view and interact with the system using the same modality (eye sight). This is illustrated by P30, "I'm just interacting with the whole program with my eyes mostly so just continue on with my gaze".

- Some participants found it easier to look than to talk.

- Alternatively, one participant was able to focus better using gaze, as illustrated by P25, “I guess, just like less work to do, less effort, it’s easier to just look than to speak. Yeah, and I can keep more concentration on what I’m trying to do. .... Because I guess when I’m talking ’cause. How should I put this. Like yes when I’m just looking at the button it averts my gaze, but like when I’m looking at the button I can- I don’t have to focus on the button, but I can kind of like think about what I’m trying to do or like what I have to do next”.

However, there were some concerns with the gaze:

- The dwell took too long to trigger, alternatively unintentionally interacting with the system.

- Participants had to shift their focus from their work to interact with the system.

- Caused eye strain to stare at holographic buttons.

The benefits of touch were noted as:

- An intuitive way to interact with floating buttons

- Found pressing holographic buttons novel and interesting.

However there some concerns with touch:

- A major drawback was having to drop the beadwork from the user’s hands to interact with the system. This is illustrated by P25, “I found that, in order to touch you, I’d have to remove my hands from the beads and the stringing. And then that’s just like I don’t know. I just found that not to be worth it”.

- Some participants were having issues using touch in AR as the buttons were not as reactive as they thought they would be. This could be due to a lack of experience using headworn AR.

- The interface was far from their place of work, participants had to put a lot of effort in to move their hands to the interface.

M.4.2 Strategies Built

Ten participants got comfortable with bead weaving during the first trial, and were more comfortable experimenting with strategies during the second trial. These include:

- Memorizing the patterns, as illustrated by P9, “I was just memorizing the patterns and then going off of that”.
- Picking up the beads directly with the needle, P10 “figuring out that I didn’t have to pick up each one and I could just get them on the needle”.
- Minimizing the pulling of the thread for both the stringing and threading actions, as shown by P3, “for the second one I realized I don’t need to take a bead and then go to the string and then like pull it and then get a bead and then go to the- I mean I realize that I can do them like together, like get a bead and put it with my hand into the needle and then go through the previous bead and then when I before I pull the needle out while the needle is in the bead”.
- Managing tension, as illustrated by P28, “I found the tension in the second trial definitely helped like keep everything together”.
- Maintaining structure of the beads, as shown by P24, “I just felt I just learned one thing that in bead weaving I had to like maintain the structure of the beads so that I don’t, for example, like if it is going to be a triangle I need to maintain the triangle to get the other structure down like other design”.

M.4.3 Positive Feedback on Interface

I received positive feedback on varying aspects of the system as a whole. I selected a few quotes which highlight the key positive feedback. P1 illustrates the enjoyability of the interactivity provided by EmbodiAR, “the interactiveness was absolutely good. This this thing is amazing too, Yes, I mean this is this [HoloLens 2] is OK, but the features that the way it [System] interacts, that that’s what got me”. P15 illustrates the potential of the system being able to replace a human instructor, “I would say it would actually reduce the human effort like let’s suppose like if if someone has to teach me, he has to like invest some of their time in getting this done and this actually removes the human effort".

A selection of the participants that did very well on the beadwork had previous experience on other forms of craft. When prompted how the learning materials encountered from EmbodiAR compared to the learning materials they used in the past, they had very positive feedback for the underlying design. This is illustrated by P9, "I think overall this was more helpful. Especially because there was three separate resources, but like in the same place on the same screen. And so I think that before really 'cause they also had the voice. So like, yeah, I think that was overall more helpful and helped me pick it up quicker compared to other crafts I've picked up. Like all the other things I've done, there's been much more of a learning curve and looking at different resources like I have watched videos, but I've also had to look up diagrams and read pattern maps, whereas this was all in one place and made it really easy to cross reference". Additionally, P28 notes, "if I had this technology it would have. I think it could have helped like speed up the process of everything because sometimes it's a little confusing. Especially when you don't have like a diagram like right there. 'cause sometimes you need the diagram to like know what you're doing and what it's supposed to look like. And just having that with your hands free so you can just look around and everything was very nice. I thought it would have helped with those".