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Enhancing Creativity in Virtuality: How Annotations in Creative Support Tool Innovate Design Ideation in Virtual Reality

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Figure 1: Illustration of our Phase 3 Study (a) Room Design Settings with our proposed ***AsynCreativity***, investigating the use of annotations across three ideation activities. (b) **Sketching:** Involves OpenBrush for writing and sketching and model library functions (**textual** and **visual** annotations); (c) **Searching:** Utilizes the seamless referencing via screen streaming widget and AI-assisted image generation via Text2Image and Image2Image (**visual** and **referential** annotations); (d) **Presenting:** Employs audio annotation tool and version control to facilitate asynchronous collaboration support (**audio** annotation).

Abstract

Asynchronous design ideation is increasingly vital in virtual reality (VR) environments. Annotations, referring to notes, marks, or comments overlaid on virtual designs, are essential for providing context, feedback, and clarity, facilitating communication among designers using Creativity Support Tools (CSTs) in the design sector. However, the effectiveness of various annotation methods in enhancing creativity during VR design ideation remains underexplored. This study aims to identify effective annotation methods that promote creativity in VR-based design ideation, addressing the shift from traditional paper-and-pen practices to immersive environments. We adopted a three-phase approach: (1) semi-structured interviews with design experts, (2) an empirical mixed-design study with design professionals, leading to the development of AsyncCreativity, our VR CST system, and (3) a deployment study evaluating annotations via AsyncCreativity in VR design ideation. Our findings reveal that multimodal annotations, especially audio annotations, significantly enhance user engagement and creativity compared to unimodal annotations. Participants reported improved ideation experiences when utilizing diverse annotation types during ideation when searching, sketching, and presenting. Our study provides valuable insights for developing effective CSTs in VR and design field, advancing the understanding of how optimized annotation strategies can foster creativity in immersive design environments.

Index Terms: Virtual Reality, Creativity Support Tool, Asynchronous Ideation, Annotation, Virtual Environments.

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1 Introduction

The advent of Virtual Reality (VR) technology has revolutionized various fields, including creativity education and design sector [55, 56]. By providing an immersive environment, VR allows users to engage in hands-on practice within a controlled, limitless virtual canvas [21, 61]. This capability enables the creation of 3D models and fosters ideation among designers in a more creative and hyper-realistic way than traditional design [22]. In this context, Creativity Support Tools (CSTs) are becoming increasingly integral to the design ideation process, as they facilitate experimentation and innovation in ways that traditional tools cannot.

Annotations, which are *notes, marks, or comments added to virtual designs*, play a crucial role in providing context, feedback, and clarity [29, 36]. They enable designers to communicate effectively, share ideas, and document the ideation process [12, 49, 10, 1]. In traditional CSTs, annotations are a common approach to facilitate design ideation [29]. However, the integration of these tools into VR environments presents unique challenges and opportunities, particularly in enhancing creativity through multimodal annotations that support divergent and convergent thinking [54, 56].

Despite the potential of VR to transform design ideation, current literature has primarily focused on improving the usability of VR CSTs without fully exploring how creative practitioners apply these tools in real-world ideation processes [52, 9]. While some studies have examined specific aspects of creative activities in VR [43, 65, 35, 37], there is a lack of comprehensive understanding of the unique value VR brings to the ideation process and the specific challenges it presents for widespread adoption [3, 61, 13]. Furthermore, existing research often falls short of providing clear guidelines for designing effective VR-based CSTs [65, 61, 16].

Immersion in VR offers a unique opportunity to enhance design ideation by providing a hands-on, limitless 3D canvas for designers. In this context, annotations in VR — whether visual, textual, audio, or referential — can significantly impact designers' creativity, collaboration, and experience across key ideation activities, mainly sketching, searching, and presenting. However, existing VR CSTs

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often require designers to revert to reality to access or create annotations, disrupting the ideation process and increasing cognitive load [54]. Understanding the interaction between these annotation types and virtual environments is crucial for developing effective design ideation practices, especially in asynchronous settings where seamless idea sharing is necessary.

This study aims to address these gaps through a systematic research-through-design approach [68]. Specifically, we seek to identify effective ideation processes and annotation methods in traditional CSTs and explore how these can be adapted to VR environments. By analyzing the impact of different annotation types on creativity, collaboration, and user experience, we aim to understand in which contexts certain annotations might outperform others, or how the combinations of annotations are the most effective approach in design ideation. Additionally, we investigated how designers' transitions from 2D to 3D environments in VR affect their ideation processes and overall satisfaction. Thus, our research questions are: **RQ1:** What are the prevailing ideation processes (i.e., activities, methods, and annotation practices) in collaborative design , and how do these processes differ between traditional and virtual environments? **RQ2:** In what ways do shifts in designers' annotation habits and strategies from traditional 2D to VR environments affect the ideation process and overall design experience? **RQ3:** How do different types of annotations (visual, textual, audio, and referential) influence designers' creativity and experiences during design ideation in VR? In which contexts might certain types of annotations outperform others?

To address these research questions, we employed a three-phase approach involving a total of 53 participants. The first phase comprised an exploratory qualitative study with semi-structured interviews of 7 expert designers to gain insights into effective ideation practices. Following this, a mixed-design user study was conducted with 28 participants, divided into two groups, to compare traditional 2D sketching with VR tools. The final phase involved a user experiment with 18 participants using our AsyncCreativity prototype, which incorporates four types of annotations across three primary ideation activities.

The findings reveal that annotation types significantly influence creativity, collaboration, and user experience in VR. Visual and textual annotations support complex tasks but may increase cognitive load, while audio annotations enhance engagement and creativity. Multimodal annotations, especially audio annotations, were found to significantly enhance user engagement and creativity in VR compared to unimodal methods. Besides, our study highlights both challenges and opportunities in VR design ideation and CSTs, including the need for seamless integration of annotation tools to minimize cognitive load and enhance the ideation process. Our research informs art learning and design practitioners on how to optimize their workflows and fosters the integration of VR technologies into creative practices. The practical implications extend to improving design efficiency and innovation, ultimately advancing the adoption of VR as a vital tool in the design industry.

2 Related Work

2.1 Design Ideation in VR CSTs

The academic and industrial realms have observed the emergence of digital tools aimed at nurturing creativity. Frich et al. [18] classify these tools as CSTs, encompassing digital systems with creativity-focused features that positively impact users of diverse expertise levels across various stages of the creative process. Wang et al. [63] propose *IdeaExpander* to support group brainstorming by intelligently selecting pictures-based stimuli according to the conversations. Bao et al. [4] introduce *Momentum* that elicits topic-oriented responses before group brainstorming. Collaborative whiteboard tools like Miro [1] and Mural [2] have gained popularity for sharing and documenting ideas.

The VR-based CSTs expand beyond the commonly 2D-based tools used [41]. VR environments provide ample space for activities that require arranging documents and information, such as collective brainstorming and sensemaking [38]. ShapesXR is a VR creation and collaboration platform for remote teams to design in 3D space. Additionally, Liang and Nick [40] develop LeMo, a shared virtual environment that facilitates collaborative music creation. Sugiura et al. [59] propose an asymmetric spatial design tool for the architectural-scale space design where the interaction effectively enhances communication.

2.2 The Use of Annotation in Ideation and Collaboration Processes

Prior research defines annotation as virtual information attached to an existing object [64], and as an explanation or comment [29, 36]. Numerous studies have explored the impact of annotation on creativity in design processes. Research indicates that annotations can enhance user engagement and facilitate deeper understanding of complex concepts by providing context and feedback [14, 42]. In traditional environments, annotations serve as vital tools for enhancing collaborative efforts, allowing designers to communicate ideas more effectively [58, 26, 25].

Annotations also facilitates the collaboration process. An early example is the ISAAC project, which aimed to capture real-time collaboration across multiple tools and convert it into a multimedia document [27]. This led to the emergence of collaborative document editing, virtual whiteboards, design critique, and team workflow management [2, 5, 30].

2.3 Annotation Assisting Asynchronous Collaboration in Immersive Environments

Researchers also focus on the application of annotations in immersive environments. A survey of 103 articles on annotation in VR highlighted various forms of annotations [6]. Romat et al. showcased the use of a digital pen for drawing in VR environments [51], while Garcia et al. facilitated collaborative inspection in construction using text, images, strokes, and scanned text [19].

While most existing VR platforms analyze synchronous collaboration [20, 53, 28, 24], there is growing interest in exploring asynchronous aspects which involves participants collaborating asynchronously [8, 11]. Zhang et al. examined visualization methods for version control in VR asynchronous collaboration, introducing *VRGit*, which allows users to navigate versions, create branches, and reuse versions directly in VR [66]. Chow et al. highlighted the importance of multimodal support in asynchronous VR collaboration and developed *MAVRC* to address social behaviors and workspace awareness in cooperative work [11]. These advancements in asynchronous creative collaboration, including new tools and techniques, inspire our focus on this topic and its potential in VR.

2.4 Multimodal Annotations in Design Processes

Kress et al. proposed the Multimodal Discourse framework [33], emphasizing that meaning is created and conveyed not only through language (text and speech) but also through various symbolic resources, including images, color, sound, motion, spatial layout, and typography. Each mode operates as a distinct symbolic system, and they work collaboratively. Researchers explored multi-modal support, such as integrating speech into workflows [31]. Studies have shown that multimodal annotations—combining text, audio, and visual elements—can significantly improve collaboration and creativity in design tasks [47, 32].

[1]https://miro.com
[2]https://www.mural.co/

In summary, while VR has the potential to enhance creative collaboration, the transition to this medium introduces unique challenges and opportunities that require further examination. Additionally, there is limited research on asynchronous annotation tasks. Current studies do not sufficiently support multimodal interactions, resulting in gaps in user experience and the effectiveness of ideation. In this study, we aim to address these gaps and contributes to understanding the role of annotations in fostering creativity in emerging technological contexts.

3 Methods

Dourish proposed concept of embodied interaction[17], highlighting the significant impact of experience and practical activities on cognition, emphasizing the symbiotic relationship between humans and technology [39]. A similar idea is present in distributed cognition[50], which underscores the influence of collaborative activities on cognition. Thus, by learning from and observing stakeholders' experiences in group practices, we can better design technology to align with users' cognitive needs. Together with the concept of *research through design*[68], this study was structured around our research hypotheses (see 3.1) and employed a **three-phase approach**, engaging a total of **53 participants**. Figure 2 depicts the study process.

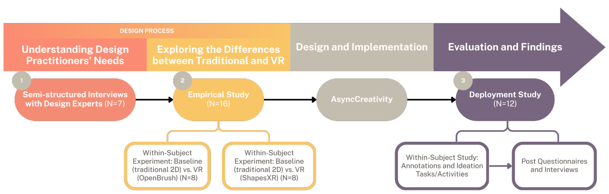

Figure 2: Flowchart of study methods and design for *AsyncCreativity*.

The initial phase was **an exploratory qualitative semi-structured in-depth interviews** with 7 experts in the design field (see Section 3.2), aimed at understanding practitioners' needs and the existing annotation practices commonly found in the design ideation process (RQ1). This phase provided foundational insights into the current landscape of design ideation. Following this, **an empirical mixed-design study** (see Section 3.3) was conducted with 28 participants from the design sector. This phase sought to elucidate the challenges and transformations associated with transitioning from 2D to 3D ideation and annotation practices (RQ1, 2). Drawing from the insights in these phases, we designed **AsyncCreativity** (see Section 3.4), a VR CST system to enhance the ideation process through innovative annotation strategies. To investigate the impact of different annotation types - *visual*, *textual*, *audio*, and *referential* - on designers' creativity and collaboration during core ideation activities, we implemented a **deployment study** with 18 participants via AsyncCreativity (see Section 3.5). This experiment focused on three major tasks in the design ideation process: *searching*, *sketching*, and *presenting*, in conjunction with the four annotation types (RQ2, 3). Our experiments conducted in Phase 2 and Phase 3 were approved by the Hong Kong University of Science and Technology's Institutional Review Board (HREP-2023-0296).

3.1 Research Hypotheses

We had the following hypotheses based on our research questions:

- **H1:** The main ideation processes in Creativity Support Tools (CSTs) involve specific activities, methods, and annotation practices that aid design ideation. However, adapting these practices to VR introduces challenges related to spatial interaction and complex user interfaces.
- **H2:** Transitioning from traditional 2D to VR environments significantly alters designers' annotation habits and strategies, such as sketching ability. These changes can either enhance or hinder creativity, depending on how well the new practices align with designers' workflows and cognitive processes. Effective strategies can improve the overall process.
- **H3:** Various types of annotations—visual, textual, audio, and referential—impact designers' creativity, collaboration, and experience during key activities (sketching, searching, and presenting) in VR. Factors like task complexity and user familiarity with VR will influence how effective these annotations are. Multimodal annotations (e.g., combining audio with other types) may be more effective than unimodal annotations for many tasks in VR.

3.2 Phase One: Exploratory Study to Understand Practitioners' Needs and Existing Annotation in CSTs

3.2.1 Participants

The exploratory study involved seven professionals (P1-P7) with substantial experience in various design-related fields. The participant group comprised product designers (P1, P2, P7), brand designers (P3, P4), an architect (P5), and a design educator (P6). Their professional experience ranged from 2 to 10 years (M=6.3, SD=3.1). This diverse expertise provided a comprehensive perspective on the ideation processes and annotation practices within traditional creative support tools (CSTs). Here we focused on sharing from experienced stakeholders. Thus, note that the experts involved in this phase come primarily from traditional design sectors and had limited experience with VR, which led us to conduct subsequent studies that incorporate insight from individuals with expertise in VR. This gap arises because VR is an emerging technology in the design field, resulting in a lack of understanding among traditional, experienced designers.

3.2.2 Data Collection and Procedures

Data were collected through semi-structured in-depth interviews via Zoom[3], each lasting from 30 to 60 minutes and a total of over 31,150 words of transcription. The sessions began with an introductory presentation on CSTs and the current state of VR-based CSTs, delivered in slides format. The interviews were conducted by two researchers and focused on four primary aspects: (i) the application of collaborative ideation in their field; (ii) the annotations, methods, and tools used for ideation; (iii) challenges faced and solutions employed; and (iv) perceptions of VR as a collaborative ideation tool. This approach ensured a thorough exploration of the participants' insights and experiences.

3.2.3 Data Analysis Approach

The interview data were analyzed using thematic analysis to identify key themes and patterns related to practitioners' needs and existing annotation practices in CSTs. Transcripts were meticulously reviewed and coded to extract insights into current ideation workflows, challenges with existing tools, and opportunities for integrating VR into the design process. This analysis informed the subsequent phases of the study by highlighting critical considerations for designing effective VR-based CSTs.

3.3 Phase Two: Empirical Study to Explore the Differences on CSTs and Annotations between Traditional and VR Environments

3.3.1 Participants

For the empirical study, two parallel within-subject experiments were conducted with 28 participants from the authors' university to

[3]https://www.zoom.com/

compare traditional collaborative ideation methods with those using virtual reality (VR). Most of the participants were from design disciplines (industrial design, interaction design, architectural design, N=18) and computer science (N=8), with the majority having experience in using VR (N=26). This selection aimed to identify deficiencies in current VR applications supporting the design process from diverse perspectives and to gather requirements for future tools, as discussed in Section 3.2.

The first experiment compared the traditional method using a 2D online whiteboard (*Miro*) with the VR application *OpenBrush*[4], involving eight participants (6 female and 8 male). The second experiment compared the baseline (Miro) with the VR application *ShapesXR*[5], with an additional eight participants (6 female and 8 male).

3.3.2 Data Collection and Procedures

Here we describe in terms of setup, apparatus, and procedures.

***Setup**:* The study was conducted in a design studio at the authors' university. In both experiments, participants were assigned to pairs and tasked with collaboratively designing a simple object using both the 2D baseline and the assigned VR platform. Participants experienced both conditions in a randomized order to mitigate potential learning effects.

***Apparatus**:* For the baseline condition, participants utilized a laptop alongside traditional tools such as pencils and markers. In the VR condition, the Oculus Quest 2 was employed as the VR headset, providing a resolution of 1832 x 1920 pixels per eye and supporting six degrees of freedom (6DOF). Participants using *OpenBrush* shared a single VR headset due to its single-user operation, while pairs using *ShapesXR* were equipped with two headsets to facilitate concurrent co-creation.

***Procedures**:* Participants were grouped into pairs and provided informed consent prior to the commencement of the study. Each pair experienced the two experimental conditions, as shown in Figure 3, in a randomized order to minimize potential learning effects. To ensure distinctiveness between the conditions, a different design brief was assigned to each. For example, designing a mug in the traditional 2D environment and a bottle or vase in the VR conditions. Figure 3 portrays our study procedures in Phase Two.

Figure 3: In Phase Two, participants paired in two to experience (a) the VR ideation; (b) discussion and sharing; and (c) traditional baseline ideation.

In the randomized first condition, participants took part in a 20-minute ideation session, followed by 5 minutes to share their design outcomes and discuss their processes. They then completed a 5-minute questionnaire to collect quantitative data on their experiences. A 10-minute semi-structured interview provided deeper qualitative insights. After a 5-minute break, participants moved to the second condition, repeating these steps. This structured approach allowed for a thorough evaluation of the collaborative design experience in both traditional and VR environments.

3.3.3 Data Analysis Approach

Data were collected through a combination of quantitative and qualitative methods. Quantitatively, we conducted the NASA Task Load Index (NASA-TLX) to assess subjective task load.

Following the questionnaire, semi-structured interviews were conducted with open-ended questions designed to elicit (i) participants' perspectives on collaborative design differences between traditional methods and VR, (ii) benefits and barriers of VR collaboration, (iii) desired features in current VR platforms, and (iv) preferences for future design methods. Additionally, researchers observed participants' design processes, taking notes on any notable events of interest throughout the experiments.

3.4 AsyncCreativity

Based on Phases One and Two, we gathered insights from practitioners to identify key annotations for asynchronous design ideation and to explore the opportunities and challenges of applying these methods in VR applications. To examine the proposed hypotheses and assess the impact of the annotations, we developed ***AsyncCreativity***, a VR creativity support tool grounded in our formative research.

AsyncCreativity equips participants with four distinct annotation methods: **visual**, **textual**, **audio**, and **referential**. The four annotation methods were derived from our Phase One and Two studies, AsyncCreativity changes these annotations into the VR ideation scenarios with its own features (see Section 3.4.1). The system allows for flexible content creation, enabling participants to manipulate visual elements, integrate textual notes, record audio messages, and reference on multiple sources, enriching their ideation experience.

3.4.1 AsyncCreativity Design Features

Based on the open-source framework *OpenBrush*, which offers hand-drawing and model manipulation capabilities, we integrated several newly designed features into AsyncCreativity:

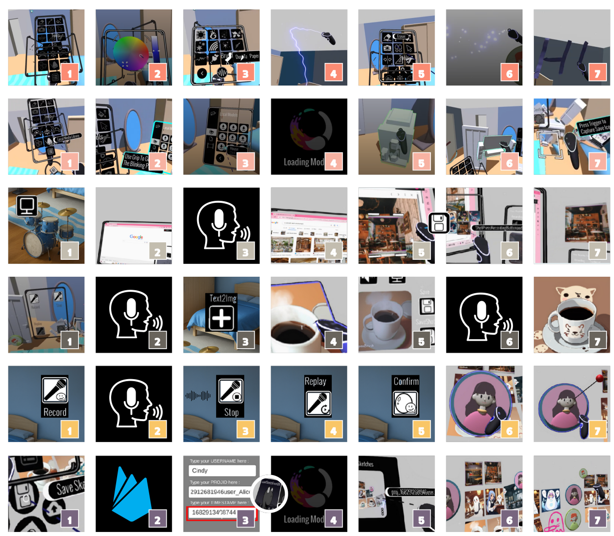

Figure 4: AsyncCreativity's design features and its interaction pipeline, from top to down in rows, writing and sketching; model library; seamless referencing via screen streaming widget; AI-assisted image generation; audio annotation and memorandum tool; and asynchronous collaboration support (according to the colored boxes).

Seamless Referencing via Screen Streaming Widget. Our research indicates that switching between virtual and real-world environments when importing external files can disrupt the ideation

[4]https://openbrush.app/

[5]https://www.shapesxr.com/

process. To address this, we propose a screen streaming widget that enables users to access local files on their computers and seamlessly load content into the virtual environment without removing their head-mounted display (HMD). Users can drag and drop files directly into the VR scene or utilize a built-in web browser for online searches. Additionally, a capture feature allows users to import images from the web into the VR environment. This is a part of **referential annotations**, derived from the resource collection in 2D design annotations.

AI-Assisted Image Generation. With the increasing use of generative models in design workflows, we developed an AI-assisted tool that generates images based on user prompts and existing images. Users can operate in two modes — Text2Image and Image2Image — and provide input via voice commands to minimize physical strain. The generated images are processed on a remote server and returned to the user's virtual environment without requiring them to remove their HMD. This is another **referential annotations**.

Audio Annotation and Memorandum Tool. Our formative studies revealed the challenges of handwriting and typing in VR for inputting semantic information. To address this, we implemented an audio annotation feature that allows users to take notes or leave messages with minimal physical effort. Users can initiate recording with a button, encoding the audio into an 'AudioClip.' Once confirmed, audio is attached to a visual icon and can be played back easily. This is indeed an audio annotation.

Asynchronous Collaboration Support. To facilitate asynchronous collaboration, it is essential to store all annotation results and design outcomes in a shared, real-time accessible space. Our system utilizes Firebase to transmit files over the internet and establish a shared storage environment. Each conceptual project generates a unique ID based on the timestamp and user's name, ensuring reliable version control and preventing file loss or confusion. Users can download various versions of sketches by specifying the desired timestamp.

In addition, the original features in the two OpenBrush tools—***Writing and Sketching Tool.*** and ***Model Library.***—enabled users to create **textual annotations** through sketches and add models as **visual annotations** in the virtual space.

3.5 Phase Three: Deployment Study to Investigate Annotations

3.5.1 Participants

We recruited 18 participants (A1-A18: 10 male and 8 female; aged 22 to 33 years) for this study. The majority of participants had backgrounds in design (N=6) or computer-related fields (N=13), with 5 coming from interdisciplinary fields, and 2 not belonging to either category. Seven participants had no prior VR experience, while 11 were familiar with VR devices. Each participant took part in the experiment independently, allowing us to explore the usability and effectiveness of the annotation methods in a simulated asynchronous experience.

3.5.2 Dependent Variables

Both qualitative and quantitative data was collected.

System Usability Scale (SUS): We employed the SUS to evaluate the overall usability of our prototype. This scale is widely used and validated for assessing user satisfaction and ease of use, providing insights into how well participants can interact with the system[7].

Sub-System Functionality Survey (SFS): This survey was used to assess the usability of specific features within the prototype, focusing on newly added functionalities. The SFS helps identify strengths and weaknesses in individual components of the system[57].

Observation and Semi-Structured Interviews: Continuous observation and post-task interviews were conducted to gather qualitative data on user experiences. These methods provided rich insights into participants' preferences and strategies regarding annotations, complementing the quantitative data collected. During the interviews, we reviewed all virtual annotations with participants, asking them to recall their annotation objectives. We summarized all annotations (N=82) and analyzed their characteristics to draw meaningful conclusions.

3.5.3 Data Collection and Procedures

Participants were first introduced to asynchronous ideation and the annotation methods used in the study (5-10 minutes). They received a brief overview of the interior design project, where they acted as designers working with clients and stakeholders in different time zones and locations. Next, researchers demonstrated and guided each annotations, allowing participants to practice and familiarize themselves with the tools (15-25 minutes; see (1) in Figure 5).

Participants then engaged in three main tasks (20-40 minutes; see (2) in Figure 5): sketching, searching, and presenting in AsyncCreativity. They were tasked with providing feedback and suggestions on a design received from a collaborator. During the ideation process, participants used a think-aloud approach to express their thoughts. They were required to consider both the input experience and information presentation, creating at least three sets of annotations that clearly conveyed their needs.

After completing a questionnaire and semi-structured interview (30-45 minutes), participants took a break before reviewing a design from another participant (5-10 minutes; see (3) in Figure 5), simulating the asynchronous design process.

Apparatus: Participants used an Oculus Quest 2 headset connected to a Windows 11 computer with an Nvidia GTX 3080 Ti GPU via Quest Link. The VR environment was streamed to a computer for real-time observation of participant behavior.

Figure 5: In Phase Three, participants were (1) introduced to the system, (2) design, and (3) revisit the room via AsyncCreativity in an interior room design ideation project.

3.5.4 Data Analysis Approach

We employed several statistical methods to analyze the data collected, apart from the analysis of the measurements in Section 3.5.2:

Chi-Square Test was used to examine associations between annotation methods and instruction categories, providing insights into how different methods are utilized.

Monte Carlo Method was conducted with 10,000 simulations to validate the chi-square test results, ensuring analysis robustness.

Fisher's Exact Test was applied to explore the relationship between specific annotation methods and their effectiveness in conveying objectives, highlighting the strengths and limitations of each method.

4 Results

4.1 Phase One

4.1.1 Semi-Structured Interview

In our interviews with design professionals, we observed a consistent method for ideation that varies depending on the project context. All participants acknowledged that for projects without a clear client, the process begins with defining the design problem based on observable requirements. Conversely, when working with a client, the team starts with a design brief provided by the client. After establishing a broad design objective through collaboration, the team engages in divergent thinking to generate a variety of solutions. As one participant (P7) noted, "*After confirming the design objective, my team typically works on their own designs, sometimes creating over 50 different versions of sketches.*" This phase is followed by presenting concepts to the client for feedback, which facilitates a fluid exchange of ideas throughout the process.

We found that key activities in the ideation process include **sketching**, **searching**, and **presenting**. Divergent thinking extends beyond mere sketching; designers actively collect information on competitor products to better understand client needs (P1). Participants emphasized that visual imagery is preferred for communicating ideas, as it aids client comprehension more effectively than text. Assistive tools, such as AI generative tools, are utilized to help clients visualize their ideas, although they are not considered substitutes for final outputs (P1). While sketching is deemed essential, challenges in sharing sketches can lead to frustration. For instance, P2 mentioned, "*I like to sketch on an iPad, but if I need to display sketches on Miro or Figma, I have to take a photo and upload it.*" Collaboration tools also serve as effective presentation aids; P1 highlighted, "*We usually store the entire design process on the same Miro whiteboard, making our work look more fluid for clients.*" Guilford's Theory of Creativity highlights four key factors: flexibility (variety of categories), originality, fluency (number of ideas), and elaboration[23]. In this context, sketching supports originality, while searching contributes to flexibility. Together, they enhance fluency, ultimately leading to effective elaboration through quality presenting.

We identified several challenges faced by designers during the ideation process, particularly regarding reference, integration, organization, and communication. Most interviewees, with the exception of P3, emphasized the need to upload reference files in various formats. P4 stated, "*Miro cannot upload videos, which makes it difficult for me.*" Designers frequently switch between multiple applications, such as Photoshop, Miro, and Google Docs, which leads to integration and communication challenges. P2 expressed frustration with chat applications, saying, "*A single discussion may have hundreds of messages, making it hard to trace back desired content.*" The scattered nature of files and conversations exacerbates disorganization in the ideation process, as noted by P1.

We also explored the potential and concerns regarding the use of VR in the design ideation process. Most interviewees (excluding P6) recognized VR's potential for enhancing spatial awareness and creativity. However, P6 expressed skepticism about VR as an ideation tool, citing a steep learning curve and inconsistent user interfaces across applications, "*I would not recommend my students to use VR as an ideation tool at this stage because the learning curve is too high.*"

Finally, we identified four types of annotations that play a crucial role in the ideation process: **visual**, **textual**, **audio**, and **referential**. Textual annotations can take the form of reports, notes, or memos that provide essential information. Visual annotations primarily consist of sketches, which help convey concepts visually. Audio annotations include presentations and voice messages left for collaborators, adding context and clarity to the ideas being discussed. Referential annotations serve as references to relevant materials or examples that inform the design process. Each type of annotation serves a specific function, and all are equally important; however, their effectiveness can vary depending on the context in which they are used. For instance, P1 noted, "*Visual annotations help bridge the gap between ideas and client understanding,*" highlighting the importance of imagery in conveying concepts. Additionally, audio annotations can provide context and clarity that text alone may not achieve. As P3 pointed out, "*Referential annotations allow us to connect ideas to real-world examples, making our proposals more relatable.*" Overall, our findings highlight the structured yet complex nature of the ideation process, the critical role of annotations, and the challenges and opportunities presented by integrating VR into design practices.

4.2 Phase Two

4.2.1 NASA-TLX Questionnaire

Table 1 illustrates the task load measurements in traditional and immersive workflows. The results indicate that current VR applications do not reach the level of traditional workflows in various aspects, although their success levels are comparable. OpenBrush slightly outperformed ShapesXR in performance, effort, and frustration. This result highlights the existing gap in asynchronous collaboration within VR.

Table 1: NASA-TLX Results in Phase Two (N=28).

	Baseline M(SD)	OpenBrush M(SD)	Baseline M(SD)	ShapesXR M(SD)
Mental Demand	34.3 (30.21)	55.7 (22.65)	35.0 (26.52)	59.6 (16.53)
Physical Demand	23.7 (23.36)	59.7 (22.54)	18.2 (18.19)	52.5 (20.42)
Temporal Demand	33.0 (22.64)	42.3 (26.70)	40.7 (19.26)	39.3 (19.90)
Performance	56.3 (23.63)	54.0 (24.85)	65.7 (24.85)	45.0 (22.99)
Effort	36.7 (21.19)	42.0 (24.55)	37.5 (21.69)	59.6 (15.64)
Frustration	27.3 (24.00)	41.7 (28.85)	23.9 (24.94)	49.3 (23.89)

4.2.2 Semi-Structured Interview and Observation

Aligned with Phase One, we observed that the annotations are usually came in form of visual, texual, audio, and referential. Annotations aided participants in recalling their thought processes and expressing ideas to collaborators. However, immersive platforms underutilize these features, with OpenBrush allowing only text writing and ShapesXR supporting both brush writing and text input. Interruptions during the design process disrupted participants' focus, particularly in OpenBrush's turn-by-turn mode.

All participants expressed mixed feelings about using VR for collaborative design. Many recognized the advantages of VR in visualizing large-scale designs and enhancing creativity. However, challenges such as the lack of intuitive file upload functionality and the need for seamless communication hindered the collaborative process. Participants noted that VR tools should facilitate better integration of external resources and improve annotation features interpretation to enhance understanding and communication among team members.

We also confirmed the findings in Phase One about the three key activities and four annotations with all the 28 participants. They further elaborated and provided us how these annotations can be in VR. Thus, we concluded the design features of AysncCreativity with these findings (see Section 3.4.1).

4.3 Phase Three

4.3.1 System Usability Scale (SUS)

We assessed the usability of our prototype using the System Usability Scale (SUS), achieving a 100% conclusiveness score from 18 participants (M=75.83, SD=12.57). Our prototype outperformed 73% of systems in the SUS database. Participants described it as 'good' and 'acceptable,' indicating willingness to frequently use the prototype for tasks, perceiving it as well-integrated and consistent. Figure 6 illustrates the detailed SUS results.

4.3.2 Sub-System Functionality Survey (SFS)

The Sub-System Functionality Survey focused on newly added features, excluding previously validated functionalities in OpenBrush like writing and sketching tool and model library.

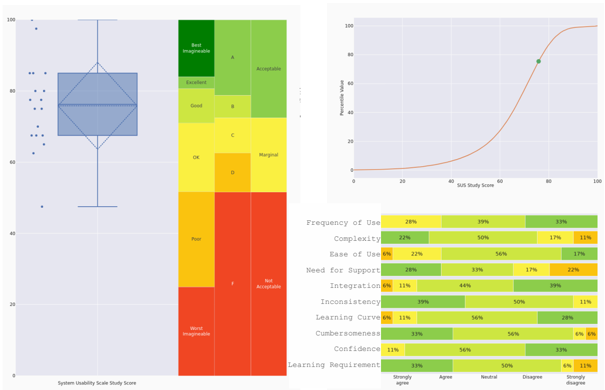

Figure 6: Results in System Usability Scale (SUS).

Audio annotation feature received the highest usefulness score (M=1.89, SD=0.323) and ease-of-use score (M=1.83, SD=0.383). Other features were positively evaluated in terms of both usefulness and ease of use; however, the seamless referencing via the screen streaming widget raised concerns regarding ease of use (M=0.944 SD=0.938), despite participants acknowledging its usefulness (M=1.22, SD=0.943). They reported onboarding challenges, indicating the need for enhancements in interaction design. Figure 7 depicts the detailed scoring in SFS.

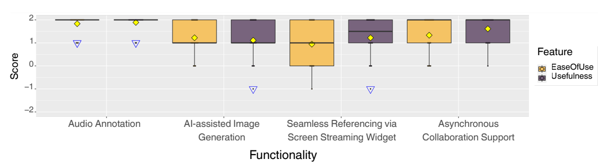

Figure 7: Our Results in Sub-System Functionality Survey(SFS).

4.3.3 Relationships Between the Annotations Features

In our analysis of 82 annotations from 18 participants, we observed distinct relationships between annotation types and the core ideation activities: searching, sketching, and presenting. The findings indicated that multimodal annotations (using two or more modalities) were more prevalent than unimodal annotations, with bimodal annotations occurring 43 times and trimodal annotations 10 times, while unimodal annotations also appeared 29 times.

Among the annotation types, audio annotations were the most frequently utilized, appearing 57 times. Textual annotations, including writing and sketching, accounted for 23 occurrences. Visual annotations (AI-assisted image generation and the model library) were used 38 times, while referential annotations(seamless referencing via the screen streaming widget) were noted 16 times. Figure 8 illustrates the relationships between annotation methods. The audio annotation tool was most frequently used in conjunction with others (N=57), followed by the sketch feature (N=34), with a majority of sketch uses occurring alongside audio (N=22). The co-occurrence frequency of the remaining features was relatively low. Significant co-occurrence relationships were observed between different categories ($p < 0.001$).

To investigate the relationship between annotation methods and objectives, we categorized the annotations (N=77, with 5 unclassified) into five types based on their objectives: *Add* (N=22), *Remove* (N=7), *Replacement* (N=21), *Modify* (N=19), and *Move* (N=8). Chi-square test result indicated a significant association between

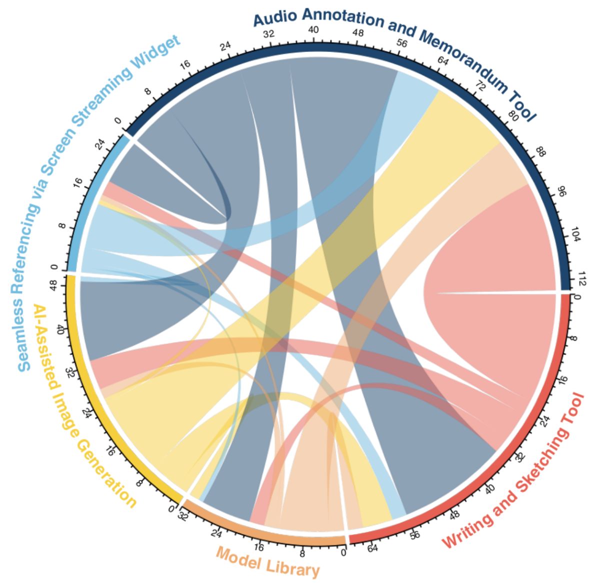

Figure 8: Chord diagram illustrating the co-occurrences of annotation methods for multimodal annotations. The thickness of chords represents the frequency of co-occurrence.

the annotation methods and the annotation objectives ($p < 0.001$). To mitigate potential errors, we employed the Monte Carlo method, performing 10,000 simulations, which also yielded significant results ($p = 0.0011 < 0.01$). By conducting a Fisher's Exact Test on the different annotation methods, we found that sketch(p = 0.0184 < 0.05), model(p = 0.0026 < 0.01), and AI-assisted image generation(p = 0.0004 < 0.001) exhibited significant differences across various objectives. However, audio annotation(p = 0.0516) and the screen streaming widget(p = 0.4717) did not show significant differences. We hypothesize that audio annotation and the screen streaming widget may have more universal applicability across different use scenarios.

In summary, our results highlight the prominent role of audio annotations in enhancing communication during design ideation, especially in contexts requiring detailed instructions. The findings also suggest that audio annotations and referential annotations, can be effectively utilized across a range of tasks.

4.3.4 Observation and Semi-Structured Interviews

Through observations and semi-structured interviews, we identified key user behaviors and preferences regarding annotation methods. Participants identified writing and sketching tool as the most intuitive method for inputting symbols during the traditional design ideation process. They effectively utilized sketches to indicate movement paths, item removal, and spatial areas, demonstrating the method's versatility. Additionally, the ability to convey abstract concepts through brush effects significantly enhanced the annotation experience, allowing for a more expressive and engaging form of communication. However, participants encountered challenges when importing via model library. They expressed concerns about the impracticality of creating a universal library of models, which often led to increased cognitive load. While basic geometric shapes were suggested as potential solutions, they were still viewed as cumbersome. Furthermore, detailed models were perceived more as design outputs rather than effective annotations, thereby limiting their utility in the annotation process. Participants showed a clear preference for web search tools than AI-assisted image generation.

They found these tools particularly effective for locating specific items or concepts. However, they expressed concerns about the ability to accurately articulate prompts for AI-generated image, but they acknowledged its usefulness for abstract or complex content. Multiple participants (N=6) indicated that integrating LLMs into the application for multi-turn conversations with users could enhance the precision of prompts in future work especially for users without prior VR/AI experience. Audio annotation emerged as the most favored method among participants, receiving praise for its clarity and ease of use. They valued its capacity to convey nuanced information without imposing significant cognitive load, comparing to typing in VR and writing in mid-air. Attaching audio to the avatar model for free manipulation significantly reduced their task load while maintaining the information clarity. Although one participant(P10) raised concerns about self-exposure, Other participants noted that the audio tone helped them better identify the source, despite the avatar model. Our feedback indicated that the Asynchronous Collaboration Support meets the needs for version control and retrieval, and it was suggested that future designs should enable comparisons of content across different versions and trace specific changes.

In VR research, users often struggle with errors in fine manipulation and the high physical demands that lead to increased task load. However, participants reported that our features alleviate these issues by allowing only coarse manipulation in VR, substituting voice input for text, importing external materials without removing the headset, using AI-generated images to reduce complex mid-air sketching, and managing versions in the backend to avoid project packaging; while maintains a high density of accurate information transfer.

The feedback from participants highlights the significant impact that various types of annotations have on designers' creativity, collaboration, and overall experience during key activities in VR. Many participants noted that multimodal annotations, particularly the combination of audio with visual elements, enhanced their ideation experiences. For instance, A5 remarked that using audio annotations while sketching allowed for a more fluid expression of ideas, effectively conveying thoughts alongside visual representations. A9 emphasized how combining visual references with audio explanations improved their understanding of tasks, likening it to having a productive conversation with their sketches.

Participants also pointed out that the complexity of design tasks in VR can be overwhelming, but employing diverse annotation types helped break down ideas and facilitate clearer communication. This sentiment was echoed by those (A2, A8, A10) who found that using audio to describe their sketches not only clarified their intentions but also fostered a more engaging collaborative environment. Overall, the insights from participants suggest that the effectiveness of annotations is influenced by factors such as task complexity and user familiarity with VR. The ability to switch between different annotation methods appears to significantly enhance the ideation process, encouraging creativity and improving collaboration among team members.

Finally, participants demonstrated a strategic approach to selecting annotation methods based on their annotation objectives. Hand-drawn writing and sketching were preferred for instructions related to "remove" and "move" during the sketching activities, while audio annotations were utilized as supplementary clarifications for images and models .

5 Discussion

5.1 Ideation Processes in CSTs (RQ1)

In our investigation of collaborative design teams (CSTs), we identified three core ideation activities: sketching, searching, and presenting . These activities underscore the essential processes that designers engage in during collaboration. However, our findings reveal that current CSTs exhibit limitations in facilitating reference searching and presenting, often necessitating the use of multiple tools to achieve comprehensive ideation. This fragmentation is particularly evident when comparing traditional 2D environments to virtual reality (VR) settings.

The unique characteristics of VR devices hinder replication of functionalities available on computer platforms, leading to distinct differences in ideation processes. For instance, sketching in 3D allows designers to manipulate the spatial position of their drawing tools directly, eliminating the need for theoretical considerations of perspective. This contrasts sharply with the 2D representation of 3D objects, which often requires extensive theoretical learning [46]. Furthermore, while reference searching on computers involves browser-based operations and local file access, VR environments present challenges due to limited interaction capabilities. Users often need to remove their headsets to access external information, highlighting the need for seamless data transmission between computer systems and VR headsets [46, 67].

Additionally, the precision of VR controllers does not match that of computer mice or drawing tablets, making tasks such as annotation more challenging. To address this, our research emphasizes the potential of audio annotations as a means to reduce physical strain while effectively conveying semantic information, aligned with [34, 48]. Lastly, documentation in VR CSTs must accommodate various media types, including 3D models and point clouds, while ensuring that spatial information is preserved and updated in remote databases.

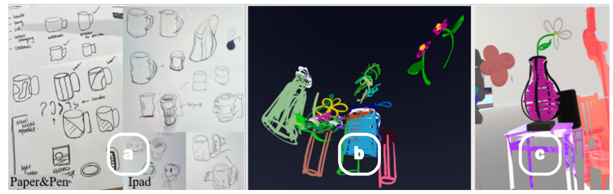

Figure 9: Sample of our particpants' sketches annotations: (a) traditional 2D sketches (baseline); (b) OpenBrush; and (c) ShapesXR.

5.2 Shifts in Designers' Habits: Traditional to VR Environments (RQ2)

5.2.1 Differences in Ideation Processes Between Traditional and Virtual Environments and Insights

The shift from traditional 2D environments to VR has led to notable changes in designers' habits and workflows. Participants expressed excitement about the immersive 3D sketching experience, finding it more intuitive. However, they faced challenges in applying their 2D sketching skills to 3D [64]. For instance, while wireframes are common in 2D, designers had to adapt in VR, often using prefabricated models or trying new techniques. Figure 9 shows examples of participants' drawings, highlighting differences in ideation. This shift emphasizes the need for design education to keep pace with technological advancements [45].

Participants also encountered challenges when switching between virtual and traditional environments, which disrupted their user experience. Many preferred to stay immersed in VR, avoiding file imports and reference searches typical in traditional setups. This behavior relates to "Visual Isolation," which describes the disconnection users feel when frequently switching environments [62]. Our system's screen streaming widget has improved integration within the VR workflow, allowing users to search and import files without breaking their immersion.

5.2.2 Changes in Annotation Strategies and their Design Opportunities and Challenges

The transition from traditional to VR environments has led to significant changes in annotation strategies, revealing both opportunities and challenges in the ideation process. As participants adapted to VR, they increasingly used multimodal annotations, combining audio, visual, and textual elements to improve communication and collaboration. This aligns with previous studies highlighting the benefits of multimodal interactions for user engagement and understanding [47, 32]. Participants found audio annotations particularly effective for providing context and clarity, helping to reduce cognitive load during complex design tasks in VR. However, challenges persist, such as the need for intuitive interfaces that enable seamless transitions between annotation types and the risk of information overload when using multiple modalities simultaneously [32]. These insights highlight the need for further research into optimizing annotation strategies in VR and developing innovative tools to support diverse user needs while enhancing the ideation experience.

5.3 Influence of Annotation Types in VR Ideation (RQ3)

5.3.1 Impact of Annotations on Creativity and Collaboration

Our third hypothesis (H3) proposed that various types of annotations—visual, textual, audio, and referential—impact designers' creativity, collaboration, and experience during key activities such as sketching, searching, and presenting in virtual reality (VR). The results confirm this hypothesis, as participants reported enhanced ideation experiences when utilizing diverse annotation types throughout the design process. A design task is inherently complex, often involving the transmission of diverse categories of information. Previous studies have primarily focused on a single type of content or transmission method, neglecting the new possibilities that arise from combinations of various annotation methods. They have also overlooked the potential interaction effects between instruction categories and annotation techniques, as noted in earlier research [15].

In our study, the impact of different annotation types on creativity and collaboration emerged as a critical area of focus. We found that participants strategically selected annotation methods based on the nature of the instruction being communicated. For instance, hand-drawn symbols were favored for instructions related to "remove" and "move," while audio annotations served as supplementary clarifications. This strategic selection underscores the importance of audio annotations in facilitating clear communication of intent during the design ideation process.

5.3.2 Future: Annotate an Annotation

Moreover, our research revealed that audio annotations often function as "annotations of annotations," supporting real-time collaboration by providing context and clarification for visual information. This phenomenon aligns with Dual Coding Theory, which posits that imagery and verbal information are processed through distinct cognitive channels [44]. The integration of visual and audio elements enhances understanding and retention, suggesting that effective annotation strategies can significantly influence the ideation process [60]. Overall, these findings highlight the need for design tools that support multimodality annotation strategies, as they can foster creativity and collaboration in VR environments, ultimately improving the overall design experience.

5.4 Implications

5.4.1 Implications for VR Research

This study emphasizes the need for further exploration of how different annotation methods interact and influence the ideation process in VR. Understanding these dynamics can lead to more effective design methodologies and enhance the overall user experience within immersive environments. Additionally, researchers should investigate the cognitive effects of using multimodal annotations, as well as how these methods can be optimized for better communication and collaboration among designers.

5.4.2 Implications for CSTs Development

The development of CSTs must prioritize features that facilitate seamless transitions between traditional and VR environments. This includes enhancing the integration of audio and visual communication capabilities to support diverse annotation strategies. Furthermore, incorporating functionalities that allow for easy access to external resources, such as web searches and file imports, will significantly improve usability and foster a more cohesive workflow within VR.

5.4.3 Implications for VR Ideation

Our findings highlight the importance of fostering an adaptive mindset among designers as they transition to VR environments. Training and educational programs should be updated to reflect the new techniques and workflows that leverage the unique advantages of VR. Encouraging designers to experiment with different annotation methods can enhance their creativity and collaboration, ultimately leading to more innovative design outcomes.

5.5 Limitation and Future Work

Our current evaluation focuses solely on the unidirectional output of user annotations. In future work, we plan to incorporate users as receivers of information to assess the effectiveness of various annotation combinations. Our findings demonstrate that AI tools can assist users in visualizing content without sources; however, issues with prompt precision remain. We intend to conduct deeper research on how AI can better integrate into immersive asynchronous collaboration workflows and compare it with other AI-assisted immersive creative tools.

Moreover, our investigation did not include real-time collaboration features, nor did it address potential side effects, such as dizziness, from prolonged use. Future work should integrate real-time collaborative features and explore user experience after extended utilization.

Additionally, we plan to explore the integration of generative algorithms to facilitate the direct creation of 3D objects within VR, capitalizing on the spatial advantages offered by immersive environments. By addressing these limitations and expanding our research scope, we can further advance the understanding of ideation processes in virtual reality.

6 Conclusion

This study offers valuable insights into how annotations enhance creativity in design ideation within VR. We identified the key ideation activities as searching, sketching, and presenting by learning from stakeholders. We identified four common annotation methods and evolved these annotations to features in VR CST for the ideation process, emphasizing the need for tailored annotation strategies to improve communication among designers. Our research shows that multimodal annotations, significantly boost user engagement and creative output compared to single-modal approaches. Method selection strategy varies among different objectives and audio attached to avatar models often serves as a interpretation for other annotations. Our findings contribute to the existing literature on asynchronous collabration in VR and design ideation and highlight the potential for future research on adaptive VR systems that cater to different user needs and cognitive demands. This research aims to inform the development of tools that foster creativity and collaboration in design, paving the way for more innovative practices in VR field.

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