Toward More Comprehensive Evaluations of 3D Immersive Sketching, Drawing, and Painting

Mayra Donaji Barrera Machuca, *Member,* Johann Habakuk Israel, *Non-Member,* Daniel F. Keefe, *Member,* and Wolfgang Stuerzlinger, *Member*

Abstract—To understand current practice and explore the potential for more comprehensive evaluations of 3D immersive sketching, drawing, and painting, we present a survey of evaluation methodologies used in existing 3D sketching research, a breakdown and discussion of important phases (sub-tasks) in the 3D sketching process, and a framework that suggests how these factors can inform evaluation strategies in future 3D sketching research. Existing evaluations identified in the survey are organized and discussed within three high-level categories: 1) evaluating the 3D sketching activity, 2) evaluating 3D sketching tools, and 3) evaluating 3D sketching artifacts. The new framework suggests targeting evaluations to one or more of these categories and identifying relevant user populations. In addition, building upon the discussion of the different phases of the 3D sketching process, the framework suggests to evaluate relevant sketching tasks, which may range from low-level perception and hand movements to high-level conceptual design. Finally, we discuss limitations and challenges that arise when evaluating 3D sketching, including a lack of standardization of evaluation methods and multiple, potentially conflicting, ways to evaluate the same task and user interface usability; we also identify opportunities for more holistic evaluations. We hope the results can contribute to accelerating research in this domain and, ultimately, broad adoption of immersive sketching systems.

Index Terms—Information Interfaces and Representation (HCI), Artificial, augmented, and virtual realities, Evaluation/methodology

1 Introduction

THREE-dimensional immersive sketching is an exciting digital technology for creative 3D work and play that is becoming a popular choice for artists, engineers, designers, scientists, and laypeople to use in both professional and home settings. Sometimes also known as "3D painting", "3D drawing", or a variant of "free-form 3D modeling" (although this is a much broader category), we use *3D immersive sketching* as a shorthand and follow Arora et al. [1] to define it formally as *"a type of technology-enabled sketching where: 1. the physical act of mark making is accomplished off-the-page in a 3D, body-centric space, 2. a computer-based tracking system records the spatial movement of the drawing implement, and 3. the resulting sketch is often displayed in this same 3D space, e.g., via the use of immersive computer displays, as in virtual and augmented realities (VR and AR)." (Arora et al. [1], p. 149).*

Immersive 3D sketching techniques, applications, and artifacts have been studied and exhibited in the computing research and digital art communities for more than 30 years. This research has led to exciting advances in bimanual freehand interaction techniques, prop-based user interfaces, 3D modeling algorithms, and digital and haptic guides, which have then been applied in contexts ranging from city planning [2] to scientific visualization [3] and art [4]. Today, 3D sketching remains an active area of research. In fact, the recent widespread availability of low-cost VR/AR/MR displays, input devices, and apps has fueled increased interest within the research community and beyond.

In this context, we believe it is the right time for us researchers to re-emphasize the importance of evaluation, one of the three principles of user-centered design [5], [6]. Conducting robust user-centered evaluations of 3D sketching is a notable challenge because, similar to traditional 2D sketching, 3D sketching can be used in so many different ways and for a variety of different purposes. In user interface research, we often gravitate toward system-level A/B comparisons of the tools we create, sometimes erroneously neglecting to consider the task. Yet, 3D sketching has matured to the point where this is an inappropriate mindset. An architect or designer would never say a pencil is a "better tool" than a marker, but they may well say that a pencil is a better tool when the goal is to create a smooth, controlled curve with line weight increasing from light to heavy across the page. Another complication in evaluating 3D sketching is that both the process and the product require evaluation. Printmaking is a highly technical, often time-consuming process, but, when needed, a medical illustrator will go through this process to create an etching rather than a pen and ink illustration because there is simply no substitute for the precise line quality that can be achieved with etching. Conversely, an architect conducting early visual brainstorming or perhaps a "massing" study for a new site will reach for a tool that supports quick, gestural movements, and potentially lots of them. Like the "quick" and "disposable" properties of a sketch that Buxton highlights as useful for UI design [7], the goal here may be to experiment rapidly, externalizing spatial ideas, engaging

- *M. D. Barrera Machuca is with Dalhousie University, Halifax, Canada. E-mail: mbarrera@dal.ca*
- *J. H. Israel is with HTW-Berlin, Berlin, Germany. E-mail: JohannHabakuk.Israel@HTW-Berlin.de*
- *D. F. Keefe is with the University of Minnesota, Minneapolis , USA. E-mail: dfk@umn.edu*
- *W. Stuerzlinger is with Simon Fraser University, Vancouver, Canada. E-mail: w.s@sfu.ca*

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the human capability for embodied cognition and creativity; the "sketch", i.e., the actual artifact produced serves as a medium for design thinking [8] and can be regarded as an intermediate ephemeral representation of the solution. Now that the applications for 3D sketching have expanded to include these contexts and more, it is time to similarly expand the way we evaluate 3D sketching.

Our goal with this paper is to provide an overview and classification of existing evaluation methods for 3D sketching. Combining this with a detailed analysis of the 3D sketching process, we aim to help researchers pick the right tool to evaluate specific (aspects of) sketching tasks. We hope future researchers can use our work as a guide in designing their research questions and evaluation methods, for example, to specify more concretely which part of the sketching process a given approach evaluates, something that is not common in past work. Our literature review may also be useful in situating future work in the context of the existing literature. Finally, this paper is also a call to action for other researchers to reflect on evaluation methods, when various methods might be most productively applied, and how this may change over time as the research area matures. We summarize the contributions of our paper as follows:

- We present a literature review of 102 papers on the evaluation of 3D sketching.
- We decompose the 3D sketching process into a series of phases and sub-tasks and present a diagrammatic overview of the process that identifies important steps users may have to follow when creating a sketch, several of which have never been specifically studied.
- Finally, we propose a new 3D sketching evaluation framework based on the insights gathered from our analysis of the 3D sketching process and the literature review.

2 Literature Review

Commensurate with our focus on approaches to the evaluation of sketching, we focused on the evaluation sections of previous publications in our systematic literature review of previous work.

We followed the PRISMA methodology for our systematic literature review [9]. First, to find the corresponding papers, we searched through Google Scholar [10], the ACM Digital Library [11], Science Direct [12], and IEEE Explore [13]. For each website we ran the following queries *VR Sketching*, *AR sketching*, *immersive 3D sketching*, *3D sketching*, *3D sketching + VR* and *3D sketching + AR*. The queries *3D sketching*, *AR + sketching*, and *VR + sketching* yielded too many results to be useful. For example, there were 64,696 results for "VR + sketching" in the ACM Digital Library. One of the reasons is that the results also include previous work on CAD systems, 2D sketching, and 3D sketching using 2D inputs. We consider such work to be out of scope for the current review as it does not meet our definition of 3D immersive sketching. For example, although they are related and certainly represent exciting research, we removed papers, such as iLoveSketch [14], where users draw on a tablet or similar system, and then the application transforms their 2D traces into 3D. We also did not consider 3D CAD systems where users draw the outlines of 3D shapes in a 2D user interface, such as the work on SESAME [15], [16]. We also removed 3D sculpting systems, such as AiRSculpt [17], where users modify an object by adding/removing volumetric material rather than suggesting forms via strokes. This does not exclude all systems under the heading of "sculpting"; we include systems, such as Aura Garden [18], where sweeping body movements create marks that together define a form, even if the authors describe the techniques as sculpting or 3D modelling. Figure 1 shows the queries utilized and the number of publications found through each query. After removing duplicates, we identified a total of 171 publications to consider.

TABLE 1
Overview of Search Query Results.

Query	Google Scholar	ACM Digital Library	Science Direct	IEEE explore
VR Sketching	197	20	7	50
AR Sketching	32	8	5	34
Immersive 3D sketching	60	9	3	17

Then, we reviewed each of these 171 papers in greater detail to evaluate whether they fit within our definition of 3D sketching. After discarding those that did not, we were left with 138 publications. From these, 19 papers were out-of-scope, as they used a 3D sketching system, but the main objective of the paper was not related to the act of drawing in 3D but focused on a different task. This category includes research like Giunchi et al.'s [19] work about retrieving models in VR and Hagbi et al.'s [20] work about converting 2D sketches into 3D models using AR. A further 41 papers were not identified during our first classification of the papers into categories, as they were (mostly) published while we were working on categorizing the papers. However, we included these 41 in the survey, also because we used them to verify that we were able to successfully categorize the evaluation process of 3D sketching in newer work.

From the 160 papers left, we identified each paper's overall goal, its evaluation goal, and the evaluation method(s) used. Our objective was to get a good overview of the various ways the research community is evaluating the act of 3D sketching. For example, we classified papers that present and evaluate a new UI for 3D sketching to be about "user interface evaluation." Then, we identified the goal of the evaluation, which could be to evaluate the usability of the UI, compare the performance against other 3D sketching methods, or both. After finishing this first categorization pass, we identified common themes within each category to identify sub-categories and also recorded the measures used in the evaluation, such as accuracy or drawing time. Using this information, we then refined the categories and sub-categories for our literature review. Figure 1 shows an overview of all the categories.

The next sections explain each of these categories in detail. Within each category, the discussion highlights a few examples of the works selected because they represent the first time a new evaluation method was presented or included a unique spin on previously explored ideas. For the full list of papers, please see tables 2, 3, and 5.

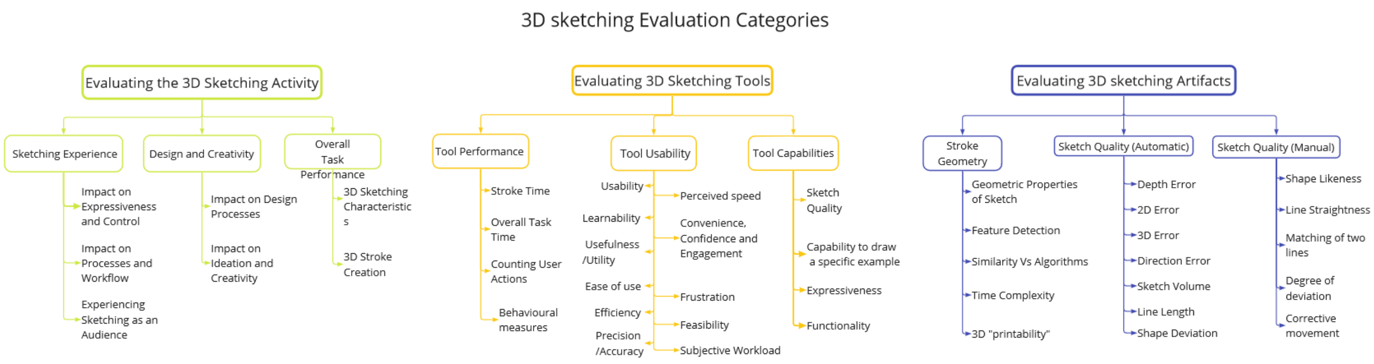

Fig. 1. Overview of the 3D Sketching Categories from the Literature Review.

2.1 Evaluating 3D Sketching Activities

In this category, the typical goal of the work is to evaluate 3D sketching as an activity, often comparing how this activity differs from traditional 2D sketching. Most of these works seek to understand how people use sketching and how sketching is different from other creative media. We identified three sub-categories for such evaluations: 1) *Sketching Experience* focuses on understanding the experience of 3D sketching, 2) *Design and Creativity* evaluates the impact of 3D sketching on the design process and creativity, and 3) *Overall Task Performance* compares the user performance of 3D sketching against other methods for creation, such as pen-and-paper. See Table 2 for a full list of papers in each category, and Figure 2 for examples covered in this section.

TABLE 2
Previous Work on Evaluating 3D Sketching Activities.

Sketching Experience	Examples	Design & Creativity	Examples	Overall Task Performance	Examples
Impact on Expressiveness and Control	[21], [22], [23]	Impact on Design Processes	[24], [25], [26] [27], [28], [29] [30], [31]	3D Sketching Characteristics - Comparison	[32], [33], [34] [35], [36], [37]
Impact on Processes and Workflow - Participation	[38], [39], [40] [2], [41], [42] [43], [44], [45]	Impact on Ideation and Creativity - Idea Creation	[46], [47], [48] [49], [50], [51]	3D Sketching Characteristics - User Experience	[28], [52], [53] [54], [55], [56] [37], [57], [58] [59]
Impact on Processes and Workflow - Art	[60], [61], [62] [63], [64], [65] [18]	Impact on Ideation and Creativity - Outcomes	[66], [67], [68] [69]	3D stroke Creation - Input Method	[70], [71], [72] [73], [74], [75] [76]
Experiencing Sketching as an Audience	[77] [43], [78], [79]			3D stroke Creation - Interaction Technique	[80], [81], [82] [83], [84]

2.1.1 *Sketching Experience*

The Sketching Experience sub-category focuses on evaluating the act of 3D sketching, often to show the potential of 3D sketching as a new medium for art and design. Typical target participants for sketching experience studies include professional designers or artists, usually in a real-world scenario, e.g., an art school or architecture studio.

Approaches in this evaluation category use qualitative evaluation methods to investigate the act of sketching in 3D. The descriptions of such evaluations range from a traditional third-person perspective description of a user study, e.g., the user created strokes with gestural, full-body motions reminiscent of dancing [62], to a first-person view, where the user talks about their experiences while sketching and their assessment of the process and its potential. An example is Grey's experience at the California State University Long Beach [60], where she used a 3D sketching tool in her own art practice. Examples of the evaluation methods used in this sub-category include interviews, observations, and questionnaires. Next, we describe the three types of exploratory studies we identified within this sub-category:

Impact on Expressiveness and Control: These studies evaluate if the user can achieve the desired artistic style when 3D sketching. An example of a research question here is if a user can emulate a real-world style, like painting with oil colours or water colours. One example of a paper in this category is Mäkelä's [23] evaluation of different techniques to see if they allow the user to draw a realistic human face. This type of evaluation is an under-explored area of research in the 3D sketching community. However, it is closely related to work in computer graphics that evaluates the rendering techniques developed to mimic specific artistic styles (e.g., oil paint, watercolor [21], [22]).

Impact on Processes and Workflow: These studies evaluate the experience of 3D sketching. Examples of research questions include how 3D sketching affects the way people think and work when designing an object [2], [43], what the 3D sketching experience is when creating an art piece [60], and what people's opinions about using VR/AR HMDs for sketching are [64]. These studies also focus on collaborative art creation or the experiences of users working together to create a sketch. For example, Rubin and Keefe [65] discuss their collaborative work to create an art piece that transgresses the border between 2D and 3D. HMDs have been utilized to present work in public art installations, e.g., Aura Garden [18]. Finally, other work uses qualitative design methods, such as autobiographical design, to design the sketching experience, e.g., Qian et al. [45].

Experiencing Sketching as an Audience: These studies focus on 3D sketch perception, i.e., how people can experience someone else's 3D sketch. Research questions in this domain include how multiple users can experience a 3D sketch at the same time and how a user without a VR/AR HMD might experience a 3D sketch. This evaluation type is under-explored but important as 3D sketches are becoming popular and are sold as art pieces [85] or shown as performances [86]. Examples include Nam and Keefe's art installation [78] and the Hybrid Campus experience [43]. Atkinson and Kennedy [79] present another approach to 3D sketching visualization; they change the experience of watching theatre by incorporating 3D sketching.

2.1.2 Design and Creativity

The design and creativity sub-category focuses on evaluating 3D sketching as a medium for creativity and design. The goal of these evaluations is to identify specific advantages and disadvantages of 3D sketching compared to other media, e.g., pen-and-paper sketching or CAD modelling. These studies can happen in a real-world setting like a designer's studio, classroom, or inside a research lab. Most evaluations use commercial applications like Tiltbrush [87] or Gravity Sketch [88]. Finally, work in this sub-category usually leverages previously proposed methodologies to evaluate the impact on creativity or the design process (e.g., AttrakDiff [89], the Creativity Support Index [90], or the Torrance Tests of Creative Thinking [91]). Next, we describe the characteristics of each such study type in more detail.

Impact on Design Processes: Such studies are about identifying how 3D sketching impacts the design process from different perspectives. Some evaluations focus on identifying the benefits of 3D sketching to support the need of designers during the early conceptual stage of design. For example, Israel et al. [25] ran a qualitative content analysis of user statements to understand the use of 3D sketching for conceptual design. They collected data for this purpose in a series of user studies that involved focus groups and a comparative user study. Other works focused on understanding how people integrate 3D sketching into their creative process. For example, Tano et al. [30] study the different features a designer needs from a system. Another example is Herman and Hutka [29], who studied the issues that 2D artists encounter in 3D sketching, and how these artists integrate 3D sketching into their creative process.

Impact on Ideation and Creativity: In this sub-category, studies identify how 3D sketching impacts user creativity. Some user studies focus on describing how 3D sketching affects the act of ideation. In other words, they study the act of forming or entertaining ideas [92]. For example, Yang et al. [48] compare 3D sketching with paper-and-pencil. Another example focuses on a specific task, like shoes [47]. Other user studies focus on analysing the design outcomes of a task. For example, Seybold and Mantwill [66] evaluate how 3D immersive sketches affect product data management systems.

2.1.3 Overall Task Performance

The goal of studies in this sub-category is to compare 3D sketching against other design methods, like pen-paper drawing or 3D CAD, to better understand the advantages and disadvantages of the new medium. These studies focus on the high-level processes of sketching, like planning the whole sketch or a stroke. As these evaluations focus on high-level processes, there is no focus on evaluating the tool, and most studies use freehand drawing, e.g., the stroke follows the hand movement without any aid or enhancement that would help users draw. Most of these studies are controlled experiments, where there is a control group and an experimental group, and there is a large range of participants, from designers and artists to university students, to people new to 3D sketching. Next, we describe the two types of task performance studies we identified from the surveyed literature.

3D sketching characteristics: Such studies evaluate the user performance of 3D sketching with the intent of gaining a better understanding of 3D sketching as a new medium for design. One important point to consider here is that most of these works use freehand sketching as a baseline for the evaluation. Examples of research questions include how VR sketching compares to other tools for design, like CAD systems [32] or pen-and-paper [36]. For example, Arora et al. [36] compared pen-and-paper sketching with 3D sketching. They found that the lack of a physical drawing surface is a major cause of inaccuracies.

Another research question involves the user experience while 3D sketching, like Perkunder et al. [52], who asked professional designers and students to sketch an object from memory and to design an object in 3D and 2D, evaluating their experiences using the AttrakDiff questionnaire [89] and the NASA-TLX [93]. A similar research question is to identify the actions users do while sketching. For example, Barrera Machuca et al. [54] investigated the user's movement behaviour while sketching and identified that, when planning a stroke, a sub-task could be to move one's head laterally to make it easier to understand the three-dimensional spatial relationships between objects. Other examples are Fehling et al.'s work [55] that evaluated how users collaborate while sketching in VR, and Thoravi et al. [56], who focused on how users learn 3D sketching. Finally, Türkmen et al. [57] evaluated the eye-gaze behaviours of people sketching in 3D.

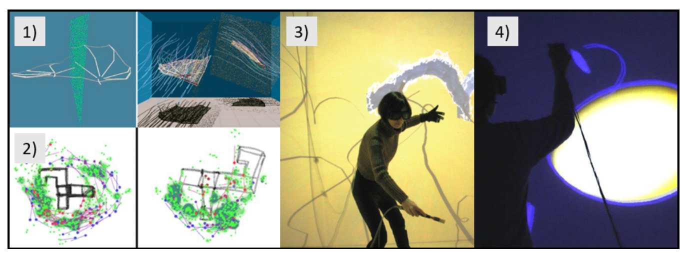

Fig. 2. Examples of previous work in the Evaluating 3D Sketching Activity. 1) Keefe et al. [26] evaluated how 3D sketching affects artists' ability to convey 3D visual design ideas to graphics programmers. 2) Barrera Machuca et al. [54] investigated the experience of 3D sketching by analyzing the movement patterns of people. 3) Keefe et al. [94] described multiple years of student and instructor experiences in response to adding 3D sketching assignments to a data visualization design course that enrolls 50% computer science students and 50% illustration students. 4) Perkunder et al. [52] evaluated 3D sketching task performance for object design.

3D stroke creation: In this sub-category, studies evaluate the different ways that users can create a 3D stroke while sketching. The corresponding evaluations often target the effect of the stroke creation method on the user actions or the final sketch. Most of these works focus on the input method, e.g., pens [73], controllers [71], hands [70], or tablets [74]. Another type of evaluation focuses on the interaction technique used to create the stroke. One example that joins both types of questions is Jackson and Keefe [82], who created 3D strokes by selecting curves from scanned 2D sketches and "lifting" them into 3D space using bimanual input from two 3D pen devices.

2.2 Evaluating 3D Sketching Tools

In this category, the goal of the work is to evaluate the influence of the 3D sketching tool, which can be either the UI as a whole or a new interaction technique, on user performance. Most of these works aim to derive insights into how people utilize 3D sketching tools to sketch and how these new tools improve user performance. We identified three evaluation sub-categories: 1) tool performance evaluations, which compare various user interfaces to identify the best one, 2) tool usability evaluations, which evaluate the usability of a user interface, and 3) tool capability evaluations, where user interfaces are evaluated based on the properties of the resulting sketch. See Table 3 for a list of each paper in each sub-category, and Figure 3 for examples presented in this section. Next, we discuss the evaluated topics and present examples for each sub-category.

TABLE 3
Previous Work on Evaluating 3D Sketching Tools.

Tool Performance	Examples	Tool Usability	Examples	Tool Capabilities	Examples
Stroke Time	[39], [95], [96] [36], [97], [98] [54], [99], [100] [101], [102], [103] [42], [57], [80] [58]	Usability	[104], [105], [106] [38], [107], [108] [4], [109], [110] [33], [111], [112] [81], [103], [113] [76], [114], [115] [84], [116], [117]	Sketch Quality	[42], [108], [115] [33], [109], [111] [59], [100]
Overall Task Time	[33], [54], [107] [98], [105], [111] [66], [100], [103] [114], [117]	Learnability	[84], [108], [118] [119]	Capability to draw a specific example - Feasibility	[40], [120], [121] [27], [122], [123] [124], [125], [126] [127], [128], [129] [117], [130], [131] [100]
Counting User Actions	[100], [111], [117] [42], [109], [114] [119]	Usefulness / Utility	[39], [122], [123] [101], [132]	Capability to draw a specific example - Professionals	[47], [53], [112] [107], [133], [134] [135], [136], [137] [45], [138], [139] [83], [84]
Behavioral Measures	[54], [68], [81] [56], [114]	Ease of Use	[59], [102], [140] [113], [122], [123] [119]	Expressiveness	[62], [102]
		Others	[99], [101], [141] [72], [95], [142] [97], [104], [119]	Functionality	[33], [38]

2.2.1 Tool Performance

User performance studies focus on evaluating the user actions with specific user interfaces or interaction techniques, with the goal of better understanding how they affect the user's actions and performance. As opposed to the Overall Task Performance category, these studies focus on the low-level processes of sketching. Such studies typically utilize A/B testing or similar evaluation methods in a research lab to better control all variables in the experiment. The target participants for user performance studies are people with different experience levels with 3D sketching. Below, we describe the three types of user performance measurements that are most frequently used:

Stroke Time: This variable evaluates how long it takes the user to draw a stroke in a specific condition. There are different ways to calculate stroke time, but the most-used definition is the time between the first and last point of a stroke. When users are asked to repeat a stroke, for example, in a tracing task, stroke time is one possible measure that can be used to compare task performance between different 3D sketching user interfaces, as in the study by Keefe et al. [39]. Stroke time is sometimes averaged across all strokes of a sketch to create a summary metric.

Overall Task Time: The task time evaluates how long it takes the user to draw a whole sketch in a specific condition. There are different ways to calculate this overall task time, with the most-used definition being the average time the participants needed to complete the task per condition. Overall task time can be used to quantify how a condition impacts the whole sketching process and might also be considered to be a rough measure of usability. For example, Jackson and Keefe [107] used overall task time to compare different sketches done by novice users using Lift-Off. Another example is HÄGGVIK [114], where they used overall task time to compare their proposed pen against drawing directly on the mobile phone screen.

Counting User Actions: Simple counting measures have also been used as evaluation metrics. For example, the number of strokes drawn [111] has been used to measure the level of detail in a sketch. The total number of deleted strokes or undo actions [114] has been used to measure how often the user failed to create the correct stroke on the first try.

Behavioral measures: Studies have also employed behavioral or action-based measures. For example, Barrera Machuca et al. [54] analyzed the properties of the final sketch to identify errors in the user's planning sub-actions. Another example is Arora and Singh [81], who quantified the physical effort of a user through their head and hand movements.

2.2.2 Usability Studies

Usability studies focus on gathering each user's opinions about their experience using a specific user interface. Their goal is to understand how people use the UI and to use that knowledge to improve the UI. When evaluating the usability of a 3D sketching UI, it is important to consider that details of the underlying implementation can dramatically impact results. For example, in AR or CAVE-based systems, spatial or temporal offsets between the pen and the stroke can significantly affect the sketching process and should thus be considered when evaluating usability. It is also important to consider that usability studies are both task and UI/interaction technique dependent, and thus there is no specific set of target participants, as participants with specific experience levels or skills might be required, depending on the goal of the study. Also, there is no standard way to run such studies nor a standard set of variables to measure.

Still, the most commonly measured variable is *usability*, which evaluates how good a UI is at doing its task. Early work that used usability to understand the user experience when using a 3D sketching system include Donath and Regenbrecht [110] and Schkolne et al. [38]. Usability measures have also been used to compare 3D sketching interfaces [115]. Other evaluated variables include the *learnability* [108], *usefulness/utility* for a specific task [123], *ease of use* [123], *efficiency* [99], *precision/accuracy* [141], and *perceived speed* [101]. Other, less common, variables include *convenience, confidence and engagement* [95], *frustration* [142], *feasibility* [104], and *subjective workload* [97].

Finally, the evaluation methods for this sub-category include surveys, interviews, think-aloud protocols, and workshops. Various questionnaires are commonly utilized: 1) the NASA Task Load Index (NASA-TLX) [93], which is a subjective assessment tool that rates perceived workload [67], [141], 2) the System Usability Scale (SUS) [143], which has been used to measure tool usability [141], 3) the Post-Study System Usability Questionnaire (PSSUQ) [144], which has been used to measure user satisfaction [145], and 4) the AttrakDif [89], which measures the attractiveness of a product [146]. See Table 4 for a list of each paper that uses each of these evaluation methods.

TABLE 4
Evaluation Methods.

Usability Study	Examples
NASA Task Load Index	[56], [67], [141], [146] [58], [80], [147]
SUS	[28], [42], [71], [76], [100], [141]
PSSUQ	[67], [145]
AttrakDif	[4], [51], [146]

2.2.3 Tool Capabilities

Tool Capabilities focuses on evaluating the ability of a UI to produce an accurate 3D sketch. Most papers compare a new sketching application with freehand drawing to achieve this. These studies typically utilize A/B testing or similar evaluation methods inside a research lab to better control all variables in the experiment. The target participants for sketch performance studies are people with various experience levels with 3D sketching. Next, we describe the three types of user performance variables we identified in this category:

Sketch Quality: These studies evaluate the quality of the final sketch. Examples of research questions include which tool produces more accurate or complex sketches. The focus is on the tool, the sketches are only used as a means to evaluate the tools. For example, in SketchingWithHands [108], the authors drew sketches that show that the user interface can fulfill their design goal. Another example is the evaluation of WireDraw [59], in which sketches created with the new UI are compared to those created with mid-air freehand drawing. For a more detailed discussion of the different ways to evaluate a sketch when the focus is on the artefact (not the tool), see the following section on "Evaluating 3D Sketching Artefacts".

Capability to draw a specific example: This method uses sketches created with the UI under investigation to evaluate its performance for a specific use case. The goal is to show that it is feasible to draw something specific. Holosketch [121] was the first 3D sketching interface evaluated using this approach. Other early work also includes Snibbe et al. [128] and Baxter et al. [123]. Different examples relied on professional artists or designers to use a system for several hours and then to describe their informed opinion about their experience. Early work used this approach to help demonstrate system capabilities, e.g., Snibbe et al. [128], Grossman et al. [112], and Wesche and Seidel [134]. This style of evaluation is specific to sketch-based user interfaces and other modeling tools where a goal model can be specified, and where the quality of the information gained is dependent upon picking a good goal that challenges users to make effective use of the new features provided by the tool.

Expressiveness: Evaluations of tool expressiveness seek to understand the degree to which a tool is capable of representing what the user wishes to sketch. For example, Keefe et al. describe their frustration with early freehand 3D sketching tools when applied to complex drawing subjects, such as scientific or medical illustration [26] and how more expressive tools, such as those utilizing more precise, bimanual drawing interfaces and including control for varying line weight, help artists and designers to use 3D sketching to address more sophisticated subjects.

Functionality: Evaluations of a tool's functionality provide insight into the success of the tool, or its features, for performing specific functions. For example, for each feature of their new user interface, Schkolne et al. [38] discussed scenarios where they found it to be useful and why.

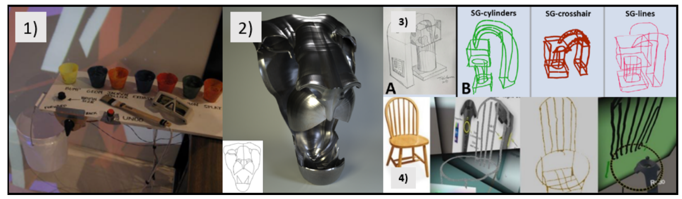

Fig. 3. Examples of previous work in the Evaluating 3D Sketching Tools category. 1) Keefe et al. [62] evaluated different interaction devices for 3D sketching. 2) Jackson and Keefe [107] used task time to evaluate user performance when using Lift-Off. 3) Barrera Machuca et al. [98] asked participants to draw the same shapes using different Smart3DGuides to identify the best one. 4) Barrera Machuca et al. [115] evaluated Multiplanes through a usability study.

2.3 Evaluating 3D Sketching Artifacts

In this category, the focus is on evaluating the final sketch. Most of these works aim to identify if the user was able to draw what they wanted or how close to a given target the sketch is. We found that some papers ask participants to draw 2D shapes like lines, cubes, and circles [36], [42], [82], [95], [97]. Other work asks participants to draw simple 3D shapes like cubes, pyramids, cones, or spheres [70], [97], [101], [114]. Finally, other works ask participants to draw 2D [42], [70], [101], [102] or 3D shapes [25], [39], [98], [107], [109], [118], [138] like cars, flowers, or vases. We identified three evaluation sub-categories: 1) stroke geometry evaluation, which evaluates the characteristics of the resulting stroke's geometry, 2) sketch quality - automatic, which computes numerical scores of the stroke quality using automatic methods, and 3) sketch quality - manual, which uses people to score the stroke quality. See Table 5 for the full list of papers within each sub-category, and Figure 4 for examples of the work mentioned in this section. Below, we discuss the evaluated topics and present examples for each sub-category. Note that these metrics are similar to the "expressiveness" category mentioned above but are still distinct. The measures discussed in this section assume a sketch was created and can now be evaluated relative to a standard, whereas expressiveness refers to a higher-level assessment of the tool's capability, i.e., does the tool provide enough expressive power to utilize it for the purpose of medical illustration? If not, then an artifact may not even exist.

TABLE 5
Previous Work on Evaluating 3D Sketching Artifacts.

Stroke Geometry	Examples	Stroke Quality (Automatic)	Examples	Stroke Quality (Manual)	Examples
Geometric Properties of Sketch	[114], [140], [148]	Depth Error	[36], [95], [96] [102]	Shape Likeness	[54], [98], [118] [59], [97], [114] [58]
Feature detection	[120]	2D Error	[71], [80], [81] [95], [96], [102] [36], [42], [72]	Line Straightness	[54], [98], [115]
Similarity vs Algorithm	[53], [130]	3D Error	[36], [39], [96] [71], [95], [116] [117]		
Time Complexity	[53], [125], [127]	Direction Error	[25], [97], [119]		
3D Printability	[53], [120], [127]	Sketch Volume	[25], [97]		
		Shape deviation	[25], [33], [109] [36], [97], [99] [81], [101], [103] [57], [58]		
		Other	[25], [39], [102] [72], [101], [119]		

2.3.1 Stroke Geometry

Stroke geometry quality evaluation focuses on quantitatively evaluating the geometry of a stroke, i.e., the vertex positions and mesh quality. The goal is to evaluate the performance of the algorithm that creates the stroke. Most of the presented techniques do not include evaluation methods with users but use specific algorithms to verify the stroke geometry instead. This research area is closely related to computer graphics, and thus we provide here only an overview of the most relevant and most-used methods for 3D sketching. Below, we describe the five types of stroke geometry evaluation techniques we identified from our survey:

Geometric Properties of Sketch: The goal of this approach is to show the effectiveness of the algorithm used to create the stroke, as, for example, in CanvoX [140].

Feature Detection: In this approach, the algorithm detects specific features of the sketch, like Brush2Model [120].

Similarity vs algorithm: In this technique, the goal is to compare new algorithms against a previously proposed one. For example, Rosales et al. [53] compared their method against other point cloud reconstruction techniques like those of Dey and Goswami [149] and Fuhrmann and Goesele [150].

Time complexity: Here, the goal is to quantify the time associated with creating the geometry. Time complexity is dependent on the geometric complexity, i.e., the number of segments present in a sketch. See McGraw et al. [127] for an example that utilizes this technique.

3D printability: This approach uses 3D printing of the 3D sketch to identify problems with the geometry. User interfaces evaluated with this method include Brush2Model [120].

2.3.2 Sketch Quality - Automatic

This category focuses on evaluating the shape accuracy of the sketch, with the goal of identifying how closely the sketch resembles the intended shape. Here we define shape as the spatial form or contour of an object. For this, the approach automatically compares the shape of the sketch to the original/target shape, using mathematically defined measures. The target participants for such studies are people with different experience levels with 3D sketching.

One important characteristic of this category is that it needs to be known what the user's goal is, and preferably, users need to know what they need to draw and, e.g., to use only a single stroke to draw it. Therefore, most studies utilize A/B testing or similar evaluation methods inside a research lab. Finally, there is a wide range of evaluated shapes, but the most common ones include simple 2D shapes like circles, squares, or triangles. For 3D shapes, most methods simplify the comparison to the area of the shape instead of the actual shape or ask participants to draw simple shapes like cubes, triangles, or curves. Next, we describe the five types of automatic evaluation techniques we identified:

Depth Error: In this technique, the goal is to quantify errors in (visual) depth between the participants' drawn shape and the shape displayed on a plane. This plane can be a 2D plane floating in space at a specific depth or a 3D free-form surface. The most common definition of depth error is the average distance in the z-direction (perpendicular to the plane) between the user's stroke and the plane. Depth error was proposed by Arora et al. [36].

2D Error: This approach quantifies the 2D error between the projected stroke and the shape displayed on a plane. The most common definition of 2D error is the average two-dimensional distance between the participants' sketched shape and the shape displayed within a plane. 2D Error was proposed by Arora et al. [36].

3D Error: In this technique, the goal is to quantify the 3D deviation of the full 3D stroke. The most common definition of 3D error is the average three-dimensional distance between the participants' drawn shape and the shape used as an example. 3D error was proposed by Keefe et al. [39].

Sketch Volume: With this approach, volume is used to quantify the similarity of the created stroke with the goal. The most common definition of a sketch volume is the smallest enclosing box for the sketch. Sketch Volume was used by Israel et al. [25].

Shape deviation: In this technique, the goal is to quantify the distortion of the sketch shape, i.e., to identify how much a sketch deviates from the ideal sketch. There are many ways to calculate shape deviation, including counting vertices [25], calculating the ratio of endpoints among all nodes [109], averaging the shortest distance from each vertex to the target shape [99], the shape uniformity [97], deviation fairness [36], proportional shape matching [101], the distance between a point on the drawn curve and the edge of a target model [103], and the curvature of the shape [81].

Other measurements: Other automatic methods to compare two shapes include calculating the directional error of the stroke [39], the line length [25], the drawing velocity [72], and the angle between ribbons [119].

2.3.3 Sketch Quality - Manual

This category focuses on evaluating the different elements of a sketch through human judgment. For example, this can concern the precision of the sketch, such as how close the sketch is to the intended one, the visual richness, the expressiveness, or the aesthetics of the sketch. Another difference between manual scoring and using automatic methods is that human coders enable the scoring of complex 3D shapes without having to know the user's goal. The target participants for such studies are people with different experience levels with 3D sketching and/or the domain.

When using human coders, it is important to consider the inter-rater reliability, e.g., ensure a degree of consistency between the scores from each coder. For this, it is often suggested to use specific scoring methods, such as the card-sort method, where scorers compare sketches with each other until they have sorted all sketches based on their quality. See Barrera Machuca et al. [54] or Tchalenko [151] for an explanation of how to use this method. It is also important to provide the coders with a rubric to follow and to hide the different conditions used in the experiment from the coders. Finally, it is important to consider the experience of the coders, as it can influence their scoring. Next, we describe the two types of manual evaluation techniques we identified:

Shape Likeness: In this technique, the goal is to evaluate how similar the shape is to the intended one as a whole–in other words, to measure the uniformity of objects [97]. There are various definitions of shape likeness, and the choice of which to use has an important influence on the scorers' assessments. Cohen and Bennett's definition [152] attempts to remove aesthetics from the evaluation. Their definition states that visual accuracy is akin to photo realism (given the limits of the medium) and that aesthetics, style, and creativity are not part of it. Previous works that use this definition include Barrera Machuca et al. [54]. Another definition of shape likeness was used by Kim et al. [118], who focus on the accuracy of defining scale and proportions. Finally, other work asked people without experience to pick the sketch they like the most or those that are more similar to the example [59].

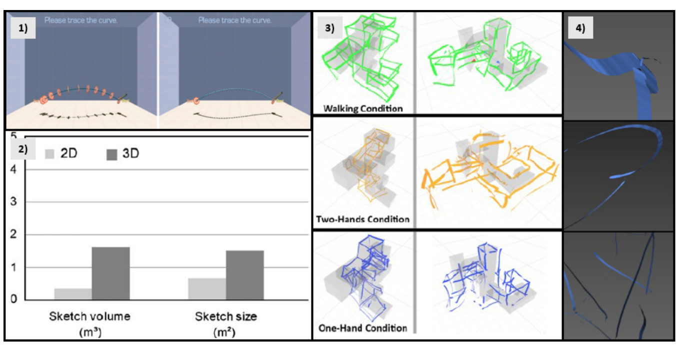

Fig. 4. Examples of previous work in the Evaluating 3D Sketching Artifacts category. 1) Keefe et al. [39] evaluated the similarity between a line the participants drew and the example. 2) Israel et al. [25] compared the difference between 2D and 3D sketches by calculating the volume and size of the sketches. 3) Barrera Machuca et al. [54] compared the difference between shapes and the model using human coders. 4) The three examples used to score the different types of line straightness by Wiese et al. [97].

Line Accuracy: With this technique, the goal is to evaluate the quality of the strokes that comprise the whole sketch. Again, the line accuracy score depends on the definition used. One definition is from Wiese et al. [97], who proposed four categories to score a stroke: 1) line straightness, 2) matching of two lines, 3) degree of deviation, and 4) corrective movements. The Multiplanes [115] system was evaluated using this definition.

3 The 3D Sketching Process Diagram

Interestingly, while performing our literature review on the evaluation of sketching, we did not run across a good description of the overall 3D sketching process nor a diagram that explains it. In addition to facilitating discussions around this topic, having a detailed characterization of the sketching process could help researchers understand how existing 3D sketching evaluations fit into the bigger picture and could also identify opportunities for future, more nuanced evaluations. Therefore, building upon the literature and our own experience, we present an initial low-level description of our understanding of the 3D sketching process.

3.1 Methodology

For our decomposition of the 3D sketching process, we took the following steps. First, we reflected on the necessary components of 3D sketching by considering the user's cognitive process, their physical actions, and the user's interaction with the UI during sketching. Each author of this document knows 3D sketching technology well and has closely tracked its application over the years. Collectively, the authors have also written or advised 10 Ph.D. dissertations, directed 25 Master's theses, published more than 50 peer-reviewed articles, and exhibited more than five invited or juried artworks on/using 3D sketching.

Our collaborative research process began with a discussion, which quickly reached a consensus on the need to look deeply at the *process* of 3D sketching, but, at the same time, raised more questions than answers as our individual backgrounds suggested different ideas to consider when describing the 3D sketching process. Within our group, we agreed that the first step was to break this process down into all necessary high-level actions, also called phases, and the corresponding sub-tasks. Based on this set of discussions, we created a timeline of high-level actions. Through an iterative process, we then subdivided these phases into specific sub-tasks that users need to perform to draw a single stroke, and we identified the actions users have to repeat to create a whole sketch. This process took place during a series of more than a dozen teleconferences. After each meeting, we set our tasks to reflect on open questions and/or to identify examples that back up our insights. In the following meeting, we then aimed to arrive at a consensus on each issue before opening a new topic for discussion.

The outcome is illustrated in an overview diagram of the 3D sketching process (Figure 5). Note that this diagram considers a wide range of the user's physical actions and cognitive processes during 3D sketching. Our contribution here is simply a first identification of many relevant aspects of the 3D sketching process, each of which could be a valuable target for future technologies to better support 3D sketching. We also identify applicable methods for evaluating each part of the process.

The diagram highlights several aspects that differ from the traditional pen-and-paper 2D sketching process. In 3D sketching, the user must conceptualize, plan, and execute 6 degree-of-freedom (DOF) motor movements, often without the aid of a surface or other physical support or guide. Another difference between the 2D sketching and the 3D

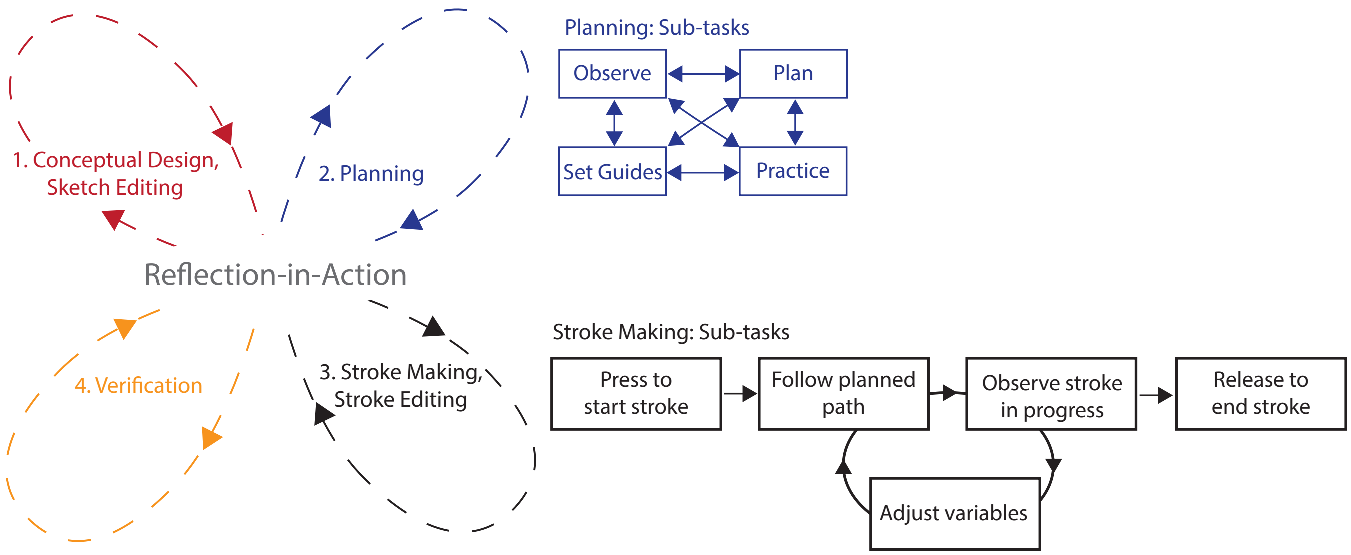

Fig. 5. Diagram of the 3D Sketching Process.

sketching processes is that users need to verify their results by spatially navigating in space, e.g., physically moving their position. Thus, 3D sketching requires accurate perception of depth and spatial orientation, not just of the subject being sketched but of the sketch itself.

3.2 Description of the 3D Sketching Process

3D sketching is an iterative process where the user needs to design their sketch, plan each stroke, draw it, and then analyze the resulting stroke to identify any new issues that may arise. This process is similar to the process of designing a new object. For example, Schön's reflection and action loop proposed an iterative process that consists of seeing-moving-seeing [153]. Similarly, McKim [154] suggested that the design process is an iterative process of imaging to synthesize one's mind, drawing to represent the synthesis results, and seeing to analyze the drawing [154]. Based on this information and our analysis, we conceptualize 3D sketching as an iterative process that consists of at least four interconnected high-level processes or phases: conceptual design/sketch editing, planning, stroke making/stroke editing, and verification. See Figure 5. Next, we describe each phase in detail:

Conceptual Design/Sketch Editing Phase: The first phase is the conceptual design/sketch editing phase, where the user reflects on the subject and aesthetic of the final sketch. In this phase, the user decides what they are going to draw and considers the composition, shape, and balance of the drawing. If the user has already drawn something, then they may decide to engage in high-level editing, i.e., thinking about changes in the composition or adding new marks to the drawing. The act of editing is vital for the generation of new ideas [155]. However, if the drawing target is given, e.g., tracing, the conceptual design phase is optional. In this phase, users may also compare the sketch with their aesthetic goals and consider appropriate changes.

Planning Phase: The second phase is the planning phase, where the user plans the individual strokes that will form the drawing. This phase is somewhat similar to the "seeing step" of the visual reasoning model [156], where the user utilizes their perception to acquire visual information that is then analyzed to understand the sketch and to generate new information. Some of the actions in this phase include observing, planning, setting guides and practicing future strokes. For example, the user will observe the current sketch from multiple perspectives while synthesizing this information mentally to identify the position and orientation of the features of the scene. Other examples include setting guides, like planes or similar surfaces or temporary marks to help the user position the elements in their sketch, planning their arm movement, or the position and orientation of the device. However, not all users do all these actions, and their order might differ depending on the user's experience and goal. This phase ends when the user knows where to position their hand in space to start a new stroke.

Stroke Marking/Stroke Editing Phase: The third phase is the stroke marking/stroke editing phase, which begins once the user starts to execute a new stroke. In theory, users should have already positioned their drawing tool in the correct position and orientation to start the new stroke, and they then only do the physical act of starting the stroke, e.g., by pressing a button or making a specific hand gesture. Then the user creates the stroke in an iterative process where the user follows the planned stroke path, adjusts their movement based on the drawn stroke, and observes their incomplete stroke to verify that the final stroke will fulfill their goal. The user repeats this cycle until they finish the whole stroke. In between following the path and observing their partially completed mark, users can adjust the position, orientation, line weight, and other elements of the stroke to match their desired outcome. This adjustment can be almost automatic or intentional, depending on how the stroke compares to the planned one. This step is similar to Norman's execution/evaluation loop [157]. This phase ends after the user finishes the stroke, i.e., releases the draw button and removes the tool from the end position. A subphase of the drawing phase can involve editing the current stroke, where the user potentially moves the stroke, deletes it, or redraws it to better match their goal. Some interactions in this editing phase include: grabbing a portion of the stroke geometry and moving it in space, and translating, rotating, or scaling the stroke.

Verification Phase: The fourth phase is the verification phase, where the user visually evaluates the current state of the whole drawing. If the result fulfills the user's goal, e.g., by communicating the target idea clearly, this means the 3D sketch is done. However, if the current drawing does not meet the user's goal, this phase is an intermediate step where the user observes the current sketch and then goes back to the conceptual design phase. The verification phase is important for evaluation, as it is only in this step that the user knows if their mental image matches the drawn sketch, i.e., if the goal of the sketching activity has been reached, i. e. "objectivation" [158] has been achieved. When verifying, inspirations can also arise - usually unintentionally - and change the future sketching process, i.e., through "back talk" [153].

3.3 Limitations

While we believe that the above is an appropriate and reasonable description of the 3D sketching process, we do not claim this is the "ultimate" description and we welcome future refinements, e.g., based on evaluations. For example, some of the involved processes are not linear, and the diagram may not capture the reflective nature of 3D sketching fully.

Further, the model currently does not take into account two important cognitive aspects: attention distribution and parallelism. Which of the steps in our process model require attention and are thus conscious [159] varies from user to user: experienced designers sketch lines without consciously thinking about them; in parallel to sketching, they reflect on the sketch. Beginners, on the other hand, concentrate on drawing individual strokes; no cognitive resources are left for reflecting on the sketch, which only takes place after a few strokes have been successfully sketched. According to their expertise, specific users may even continuously move between these two extremes.

4 Our Evaluation Framework

In this section, we present a new 3D sketching evaluation framework based on our analysis of the sketching process and our literature review of over 160 evaluations of relevant publications, where we found a heterogeneous picture in terms of evaluation approaches and procedures used. Our goal in proposing this new evaluation framework for 3D sketching is to raise awareness of the importance of systematic evaluations of 3D sketching. Our proposed 3D evaluation framework has the potential to increase the validity of evaluations in the field, for example, by enabling better comparability between new 3D sketching user interfaces. Further, it can be helpful to people interested in learning to use 3D sketching, as instructors could use the framework to provide feedback about which aspects of their sketch and sketching process the trainee should improve. Finally, the framework may be useful to researchers who wish to understand how their evaluation strategies match or complement those already used within the field or to identify under-explored research areas.

Our evaluation framework consists of three aspects that we recommend 3D sketching researchers consider in order to make informed decisions about the evaluation process. These aspects are 1) evaluation categories, which focuses on identifying which part of the 3D sketching process they will evaluate, 2) evaluation tasks, which focuses on choosing the most appropriate task for their goal, and 3) evaluation demographics, which focuses on identifying the most appropriate population to use during an evaluation.

4.1 Evaluation categories

The 3D sketching field is mature enough to support a plurality of evaluation methods due to the different uses of 3D sketching. This also means that there is very likely no "holy grail" UI for 3D sketching as one interface cannot satisfy the needs of all application domains. Based on this reflection, we do not propose a single evaluation method but promote a more holistic approach. Thus, our proposed 3D sketching evaluation framework can apply to many different application domains, regardless of their individual needs. This approach follows the work of MacDonald and Atwood, who suggested creating evaluation frameworks that consider a holistic vision of evaluation [160].

Thanks to our literature review, we identified the three main elements of 3D sketching that require evaluation: 1) Evaluating the 3D sketching activity, which is about understanding how users do the process of drawing, 2) Evaluating 3D sketching tools, which concerns understanding the user interfaces/interaction techniques that are used to draw something in a specific domain, and 3) Evaluating 3D sketching artifacts, which is about understanding the goal of the task. Figure 6 shows examples of each category.

Ideally, each new 3D sketching tool should be evaluated in each of these three categories. However, we realize that this is not always feasible. Therefore the first step for using our evaluation framework is to identify which aspects are the *most* important to evaluate in each case and to match these to appropriate evaluation strategies. Next, we describe some examples and special considerations for each of the three categories.

Fig. 6. Examples of the three evaluation categories we identified. 1) Evaluating 3D Sketching Skills: Israel et al. [25] evaluated 3D Sketching Skills. 2) Evaluating 3D Sketching User Interfaces: Keefe et al. [39] evaluated a new interaction technique called Line-Drag. 3) Evaluating 3D Sketching Artifacts: Plots used by Elsayed et al. [95] to represent how different types of haptic feedback affect user accuracy.

4.1.1 Evaluating 3D Sketching Activities

When evaluating 3D sketching activities, it is important to identify which process or sub-task of the 3D sketching process we want to evaluate and its relationship to overall process. Knowing the phase that is most relevant to the evaluation goal can help to select a good evaluation methodology. For example, for evaluations that target the **conceptual design phase**, methodologies under the *Sketching Experience* heading within the *evaluating 3D sketching activity* category might be useful since they focus on the high-level processes of the 3D sketching process, i.e., understanding how people think while sketching. Methodologies under the *design and creativity* heading within the same category might be even more useful, as they aim to understand how 3D sketching helps ideation, which again focuses on the high-level processes of the 3D sketching process. On the other hand, low-level evaluation methods, such as stroke counts, are not truly useful for the conceptual design phase. For evaluating the **drawing phase**, methodologies discussed under the *overall task performance* heading in the *evaluating 3D sketching activity* category may be useful as they typically focus on evaluating user behaviour and performance. Similar methodologies might also apply well to the **planning phase**; however, the best methodologies for this phase are less clear since only a few prior studies have focused on this phase. The downside of selecting an evaluation methodology based on the drawing phase is that it provides a narrow evaluation of just a portion of the overall drawing task, Yet, this approach is appropriate for new tools and techniques that are designed to improve specific phases of drawing.

4.1.2 Evaluating 3D Sketching Tools

When evaluating 3D sketching tools, we suggest adopting the mindset that there is no “holy grail” interface for 3D sketching in general. Rather, 3D sketching tools should be evaluated in a specific context. Evaluating the impact of 3D sketching on different domains is about finding the best tool for a specific task. One questionable approach we identified in the literature is that it is common to compare new 3D sketching tools with a base condition like freehand drawing. However, we recommend designers do not conduct A/B evaluations with systems that differ in too many factors. Often this yields only very general information, which is then often not actionable because it is so hard to understand what caused the difference.

Instead, it may be useful to study the new tool’s impact on a specific phase of 3D sketching, as not all tools will address the same challenges of 3D sketching, and these challenges might be phase-dependent. For example, when evaluating a tool for a task where accuracy is important, it may be important to consider how this tool helps users correctly identify the relationship to other strokes during the planning phase and if the user can maintain appropriate motor control of the drawing device in the drawing phase, as both actions are important for accuracy. Another example is a tool for creating new concepts, where it is important to evaluate the conceptual design phase, where most creative outputs occur.

When evaluating the impact on domains, there are several potential study types to consider, depending on the part of the 3D sketching process that is to be evaluated. When targeting the **conceptual design phase**, study methodologies under the *capability to draw a specific example*, *expressiveness* and *functionality* headings within the *evaluated 3D sketching tools* category may be useful to evaluate the high-level process of 3D sketching. For the **drawing phase**, study methodologies under the *tool performance* and *usability studies* headings within the *evaluated 3D sketching tools* category may be useful for understanding the different skills and processes users follow when 3D sketching with different UIs. Finally, study methodologies within the *evaluating 3D sketching artifacts* category can be used to evaluate the **verification phase** by comparing the results produced with different sketching UIs.

Future work should thus consider the task and 3D sketching phase when evaluating new 3D sketching UIs, as this will correctly contextualize the advantages and disadvantages of an UI over other methods.

4.1.3 Evaluating Artifacts

Evaluating the artifacts produced by 3D sketching aims to identify if the user was able to achieve their goal, which sometimes means they were able to draw what they wanted. In our literature review, we found multiple metrics to make this comparison. However, these metrics do not have a standard definition. Here, we recommend using the following definitions for the most common metrics: **Overall task time**, the average time the participants needed to complete the task per condition, which describes how long it took the participant to do the task. **2D error**, the average two-dimensional distance between the participants’ sketched shape and the shape displayed within a plane, and **3D error**, the average three-dimensional distance between the participants’ drawn shape and the shape used as an example. Both 2D and 3D errors identify the difference between the desired artifact and the produced one.

In our literature review, we found that most previous work only considers the produced sketch as an artifact of 3D sketching. In other words, previous work only evaluated the **verification phase** of the 3D sketching process. For example, studies under the *overall task performance* heading within the *evaluating 3D sketching skills* category focus primarily on the outcomes of the 3D sketching process, while studies within *evaluating 3D sketching artifacts* focus on the 3D generated sketching artifacts. However, sometimes the goal of sketching is simply to support thinking about a problem, in which case it does not matter what the sketch looks like [7], [161]. Current unexplored evaluation areas include the evaluation of the “back-talk” during the verification phase when the user sees what they had drawn and then uses that information to update the planning of their sketch. Therefore, another recommendation in this area is to develop 3D sketching systems for other uses of 3D sketching, like relaxation or meditation, that do not rely on the sketch as a product.

We found that the current maturity level of the field, where numerous commercial applications are available to the user, allows us to say that 3D stroke creation is a prerequisite for all drawing user interfaces. Regardless of the goal of the UI, for a modern 3D sketch system, a user can today expect and require a certain maturity for the ability to quickly and effectively create a stroke. Yet, there is still work that focuses solely on a) accuracy, which measures how well the user was able to draw an example, and b) efficiency, which measures how fast the user can draw the sketch, usually represented by stroke time. For example, when comparing two user interfaces, 3D error [36], [39], [71], [95], [96] is often used to identify the better one. Therefore, our third recommendation is that the research field should now move beyond focusing *only* on efficiency (time) and accuracy and also consider evaluation metrics that allow us to better evaluate other aspects of sketching. We thus encourage future work in this area to focus on metrics that show how much control a user has over their final stroke, including effectiveness, which allows us to quantify how good the user interface is for the specified application domain. In other words, if we only focus on efficiency, we might get strokes that can be misleadingly good, but the whole user interface might still not be usable in a real-world scenario. Finally, our third recommendation is to go beyond the simple measures of stroke quality and similar metrics reported in the survey, as evaluating the artifacts produced is quite application-dependent and requires close interaction with domain experts, and qualitative expert analysis and feedback will often be the better choice here.

Future work should also go beyond evaluating 3D sketching artifacts that support drawing a specific object towards artifacts that focus on the different benefits that sketching brings to the sketcher.

4.2 Evaluation Tasks

As there is not a single best tool for 3D sketching, there is no single task that allows us to evaluate every use of 3D sketching. Through our literature review, we identified a wide variety of sketching tasks based on the different scenarios and goals of each user interface and evaluation. One issue we found is that some instances of recent work seem to prefer a standardized set of 3D sketching tasks (draw a line X times) over more open and creative tasks, yet without justifying the decision to adopt this approach. This lack of justification is a problem, as the task should be highly dependent on the application domain of the user interface, and the application domain will influence the type of measures used to evaluate the user performance. For example, a sketching application for engineering and a VJ (video jockey) application that uses sketching during a live performance both have different end goals and it is not really appropriate to evaluate them with the same task.

We encourage researchers in this area to reflect more on the future uses of their interface(s), to choose an evaluation task that is appropriate, and to explain clearly why this task was chosen. Here is where our proposed 3D sketching evaluation framework is useful, as we provide an overview of the different application domains for 3D sketching, which then enables authors to specify why a given approach was chosen. Next, we provide specific recommendations about what and what not to do when choosing evaluation task:

Choosing the prototype: Do not conduct 3D sketching studies with tools that are not working sufficiently well at the technical level (e.g., bad tracking, clumsy controllers), as this will negatively impact the validity of the evaluation. It is especially important when comparing with prior 3D sketching techniques that have been described in the literature but for which modern implementations are not immediately available on an app store, e.g., like Tiltbrush [87] or Gravity Sketch [88]. To make fair comparisons with those techniques, a high-quality implementation for modern hardware is needed.

Considering Differences Between Users: When selecting the 3D sketching task, including the drawn shape, it is important to consider the individual differences between users. For example, the user's experience or spatial abilities will very likely affect their results. Or adding a time limit to the study might pressure users and also impact results. Without such considerations, it becomes challenging to interpret the results correctly, i.e., in a way that supports scientific work.

Choosing the Tasks: Since 3D sketching requires a combination of tasks (e.g., motor control, perception, and cognition), a common error involves a mismatch between task/hypotheses and the evaluation method used. For example, using an evaluation strategy that is appropriate for low-level tasks (e.g., high precision timing is good for evaluating motor control) in a study that focuses on a task where cognition is most important (e.g., creative art making).

4.3 Evaluation Target Population

Thanks to our literature review, we found that most previous work used designers, artists, architects of various experience levels, or other people experienced with VR as participants, as this population can identify and describe the difference between media. Depending on the application area, this may or may not make sense. Recruiting participants with well-developed design skills and/or prior drawing experience is an important evaluation strategy for tools designed for professional users. Yet, drawing is a skill that must be learned, and results from studies of 3D sketching with novice users who are not confident drawers, even with traditional 2D media, are not likely to provide reliable results for evaluating professional tools. On the other hand, if the tool targets novice users, feedback from professional designers may not be useful. Most of the evaluations we surveyed focused on the short-term usage of a UI, typically within an hour. Thus, we can state that longitudinal studies are generally an open topic in the field.

5 Discussion

We designed our 3D sketching evaluation framework through a literature review, by reflecting on our own experiences, and iteratively diagramming the process. The overall goal of our work is to bring attention to the evaluation process and to help future researchers choose more appropriate methodologies, tasks, demographics, and measures. It is important to note that we do not expect or recommend applying every evaluation method to a single user interface but instead using the evaluation methods that are *most* appropriate.

In our literature review (Section 2), we found that few examples of previous work explain which part of the 3D sketching evaluation process they are evaluating and also why they choose a specific evaluation method over others. Together with the many possible options to evaluate 3D sketching, this makes it quite challenging to compare different solutions. This limits the impact of a proposed new user interface or interaction technique, as people outside the field then encounter problems when trying to choose the best tool for their use case. Beyond the lack of explanations about which phase of 3D sketching is being evaluated and the goal of the evaluation, we identified the following problems.

5.1 Definition and Motivation of Evaluation Methods

We found that some papers do not describe the intent behind the selected evaluation technique or how specific evaluative measures were calculated. For example, we found at least three different definitions for drawing time, and some papers do not even define what drawing time is. Such discrepancies are prevalent when describing automatic methods to evaluate sketch quality, where almost every paper defines new metrics to achieve their evaluation objectives. Further, some of these metrics have very similar names, which means that someone without an in-depth knowledge of the area might find it difficult to know if they relate to the same metric or are different, e.g., the deviation in the z-direction [96], the mean depth deviation [36], or the depth error [102]. Beyond differences in the measures used to evaluate a sketch, there are also differences in the prepossessing of the data. Some work filters the user input to score it automatically, but others utilize the same (or similar) metrics without filtering the data. Here, we address this limitation by proposing standard definitions of the most common evaluation metrics used (see Section 4.1.3).

5.2 Usability Evaluation

There are many different ways to evaluate the usability of a user interface. For example, a person interested in using 3D sketching in a classroom setting might be looking for an interaction technique that is easy to use and precise and will find themselves comparing usability studies that use different evaluation methods (interviews vs. questionnaires vs. expert-based evaluation), different populations (designers vs. novices), and different settings (laboratory vs. design studio), which makes it challenging to derive insights. Also, some publications do not define the exact questionnaires used, which makes it again more difficult to compare between approaches. In this paper (Section 4.1.2), we address this limitation by proposing specific recommendations about how to evaluate the usability of 3D sketching tools.

5.3 The role of Result Images in Evaluating 3D Sketching

Nearly all 3D sketching research papers present images of the 3D models produced. This is critically important since the visual results achieved provide concrete evidence of the aesthetic, expressiveness, and control that was achieved. However, to serve as an effective evaluation, the context in which the results were generated must also be reported. The imagery must be contextualized, explaining the how, when, why, where, and by whom for each image or 3D model produced. Further, for visual results to provide evaluative evidence, authors must discuss and critique the visuals in a manner similar to the way the results of different shading models might be compared and contrasted in a computer graphics research paper [162] or to the way that the visual qualities of brush strokes are contrasted when comparing artworks side-by-side, e.g., [163]. Here, we address this issue by recommending which aspects of a Sketching Task should be considered when selecting it (see Section 4.2).

5.4 The Need for Evaluation

To reiterate one of the main themes of the paper, it has been more than 26 years since Deering presented the HoloSketch system [121], which many regard as the first example of what we commonly think of as 3D sketching today. Thus, 3D sketching is a mature research topic at this point. That does not mean that the research is done! However, it means that the most useful research at this point will come from studying extensions, nuances, variations, and applications, which brings evaluation to the forefront of the area. We now have the opportunity to make our research questions more precise, and our research evaluations should also become more precise to match these questions. We thus encourage future papers about 3D sketching to evaluate their user interfaces using at least one of the many approaches mentioned above. A similar approach has been taken in the 2D sketching community, where new user interfaces have focused on specific use cases like drawing developable shapes [164], symmetric shapes [165], or curves in existing 3D scenes [166]. Another class of 2D sketching work focuses on a specific task, like architectural design [167]. This call to action does not mean that every new user interface needs to be evaluated, as we recognize that there are situations where an evaluation is not required. For example, consider artistic research projects, novel techniques difficult to compare to a baseline, or research published in venues designed to foster discussions, e.g., workshops. Still, we believe that the baseline for publications in the field should be to include an appropriate evaluation, unless there is a good reason not to.

6 Conclusion

In this paper, by analyzing the 3D sketching process and performing a literature review of existing approaches, we developed a new 3D sketching evaluation framework. The framework identifies three different evaluation categories: a) Evaluating the 3D Sketching Activity, which focuses on evaluating the activity of 3D sketching, b) Evaluating 3D Sketching Tools that targets evaluating the UIs used to 3D sketch, and c) Evaluating 3D Sketching Artifacts, which evaluates the resulting drawing. Each evaluation category consists of several sub-categories that evaluate a specific aspect of 3D sketching related to that category. Finally, we discussed the current state of evaluations within the 3D sketching field. With this paper, we aim to inspire readers to consider the current limitations of and opportunities for evaluating 3D sketching.

We believe the 3D sketching field is mature enough that researchers should include an evaluation as part of their contribution. For example, today, it is likely insufficient to justify a new 3D sketching UI based on its novelty alone. Or to use a given evaluation method without reflecting if its properties match the needs of the current research question behind the work. We also recognize that evaluation is multifaceted, and it is not possible to evaluate every aspect or use every evaluation method in a single publication. Still, among the possible evaluation aspects, authors should choose the most appropriate evaluation category that matches their research question(s). This choice should also extend to the measurements used to evaluate user performance, as each measure needs to be clearly matched to the goal of the research.

In the future, we hope to see more authors create tools for specific tasks or adapt existing tools to new domains, and we expect to see fewer "generic" 3D sketching tools designed to work for all tasks. We also encourage future studies on the visual level of 3D sketching, e.g., new brushes and new shading techniques.

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Mayra Donaji Barrera Machuca Dr. Barrera Machuca is an Assistant Professor at the Faculty of Computer Science at Dalhousie University in Halifax, Canada. Her current research areas include using multimodal interactions for 3D sketching and understanding human performance with virtual objects. She also proposes new user interfaces that improve the accuracy of people working inside virtual environments. Dr. Barrera Machuca's work has generated considerable interest in the community, including winning the 2021 VGTC Virtual Reality Best Dissertation Award.

Johann Habakuk Israel Johann Habakuk Israel is a Professor of Applied Computer Sciences at the HTW Berlin. His main research areas are immersive sketching and modelling, tangible interaction, human-computer interaction, and virtual reality. He is currently involved in projects on participatory urban development (BMBF Inspirer), body schema therapy using 3d sketching (BMBF ViTraS) and virtual paleantology (Cluster of Excellence "Matters of Activity").

Daniel F. Keefe is a Distinguished University Teaching Professor and Professor of Computer Science and Engineering at the University of Minnesota. His research centers on scientific data visualization and interactive computer graphics. In addition to his work in computer science, Keefe is also an accomplished artist and has published and exhibited work in top international venues for digital art. Before joining the University of Minnesota, Keefe did post-doctoral work at Brown University jointly with the departments of Computer Science and Ecology and Evolutionary Biology and with the Rhode Island School of Design. He received the Ph.D. in 2007 from Brown University's Department of Computer Science and the B.S. in Computer Engineering summa cum laude from Tufts University in 1999.

Wolfgang Stuerzlinger Building on his deep expertise in VR and HCI, Dr. Stuerzlinger is a leading researcher in 3D user interfaces. He is a full professor in the School of Interactive Arts and Technology at Simon Fraser University in Vancouver, Canada. He has supervised more than 50 graduate students to completion and published more than 200 fully refereed scientific publications. Current research projects include better interaction techniques for 3D applications, immersive analytics, the characterization of the effects of technology limitations on human performance, investigations of human behaviors with occasionally failing technologies, user interfaces for versions, scenarios, and alternatives, as well as new VR hardware and software.