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REVIEW ARTICLE

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Sketching assessment in engineering education: A systematic literature review

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Abstract

Background: Sketching exists in many disciplines and varies in how it is assessed, making it challenging to define fundamental sketching skills and the characteristics of a high-quality sketch. For instructors to apply effective strategies for teaching and assessing engineering sketching, a clear summary of the constructs, metrics, and objectives for sketching assessment across engineering education and related disciplines is needed.

Purpose: This systematic literature review explores sketching assessment definitions and approaches across engineering education research.

Methodology/Approach: We collected 671 papers from five major engineering and education databases at all skill levels for reported sketching constructs and metrics, cognition, and learning contexts. Based on the selection criteria, we eliminated all but 41 papers, on which we performed content analysis.

Findings/Conclusions: Engineering, design, and art emerged as three major disciplines in the papers reviewed. We found that sketching assessment most often employs metrics on accuracy, perspective, line quality, annotations, and aesthetics. Most collected studies examined beginners in undergraduate engineering design sketching or drawing ability tests. Cognitive skills included perceiving the sketch subject, creatively sketching ideas, using metacognition to monitor the sketching process, and using sketching for communication.

Implications: Sketching assessment varies by engineering discipline and relies on many types of feedback and scoring metrics. Cognitive theory can inform instructional activities as a foundation for sketching skills. There is a need for robust evidence of high-quality assessment practices in sketching instruction. Assessment experts can apply their knowledge toward improving sketching assessment development, implementation, and validation.

KEYWORDS
assessment, sketching, systematic literature review

1 | INTRODUCTION

Sketching assessment is challenging, as many criteria are ambiguous, subjective, and applied in many ways (Chaudhuri et al., 2022). It also varies across engineering disciplines. Unlike computer-generated visualizations, which are formal and precise, sketches are ambiguous and informal, which makes them difficult to assess (Das & Yang, 2022). It is therefore difficult to define fundamental sketching skills and the characteristics of a high-quality sketch. As well, assessment objectives and the definitions of sketching skills have shifted over time from emphasis on producing a high-quality sketch to using sketching as a process for innovation and problem solving (Fava, 2020). Design researchers agree that sketching is essential in teaching students how to think visually when representing concrete and abstract information such as direction, proportion, or spatial orientation (Tversky & Suwa, 2009) and how to think within problem constraints by representing and externalizing components from mental representations (Sachse et al., 2004). Additional factors that complicate sketching assessment include the application of discipline-specific techniques and the role of experts in guiding and evaluating sketching. Identifying sketching objectives and metrics is necessary for studying how effectively sketching teaching and learning is assessed in engineering classrooms.

If instructors are to successfully incorporate sketching into engineering graphics and engineering design classrooms, there is a need for high-quality assessment to measure sketching skills and learning. Engineering educators have recognized the need for opportunities to practice sketching in the classroom through examples, guidelines, and assignments (Sung et al., 2019). Even with the prevalence of computer-aided design (CAD) in the classroom and professional practice, there are disadvantages to teaching engineering design and visualization with CAD alone. Computer-based design tools offer precision, accuracy, and efficiency but little support for creative thinking and ambiguity (Meneely, 2007). Software constrains students' awareness of design possibilities without ambiguity to promote ideas, questions, and deeper conceptual understanding of a design (Veisz et al., 2012). Relying on highly realistic images for idea generation during engineering design may contribute to greater idea fixation and a lack of originality (Atilola & Linsey, 2015). One solution for idea fixation is re-representation, where designers use sketches to externalize their ideas for restructuring and analytical insight (Zahner et al., 2010). Using CAD without sketching in design graphics may cause neglect of other essential visualization skills, such as spatial and geometric knowledge, and reasoning about a design before producing with CAD (Metraglia et al., 2015). In addition, freehand sketching is an effective way of developing essential spatial reasoning skills as the foundation for engineering design visualization proficiency, which CAD requires (Gagnier et al., 2017).

To inform future educational efforts and research in engineering sketching, it is important to understand what skills are assessed and how researchers and instructors are measuring them. This systematic review explores current literature on sketching assessment and identifies the fields they originate from, with emphasis on interdisciplinary research. Previous systematic literature reviews of sketching have studied freehand sketching for engineering design in science, technology, engineering, and mathematics (STEM) education (Zainuddin & Iksan, 2019) and science students' use of drawings for conceptual diagrams and models during inquiry (Chang et al., 2020), but none has examined the assessment of freehand sketching skills in engineering education. We searched for assessment criteria and practices, sketching cognition included in assessment, and wider learning contexts of sketching assessment. Including literature from art and design as well as education can broaden our definitions of freehand sketching skills, since these disciplines teach sketching more consistently than engineering. We aim to provide the engineering education community with an understanding of the definitions and assessment of sketching skills by exploring the scope of assessment methodologies and strategies for instructional practice, to lay the foundation for informed sketching assessment development and validation.

1.1 | Research questions

The purpose of this study was to examine the state of sketching assessment across disciplines to explore the variety of skills and abilities that instructors and researchers view as central to sketching. This study synthesized how sketching ability is defined, quantified, and/or assessed across the literature to understand its impact on engineering teaching and learning. We do not recommend a specific tool or approach but rather report evidence of existing assessment strategies and their effectiveness in engineering education contexts, along with validity and reliability evidence. Our goal was to understand the diversity of sketching assessment and identify its purposes in the engineering design and education literature through a systematic literature review and content analysis. We also wished to discover how cognitive theories and frameworks such as design thinking, problem solving, idea fluency, and representational thinking influenced sketching assessment. The following research questions guided our study:

1. How are sketching ability constructs assessed and measured in peer-reviewed sketching literature?
2. What cognitive theories are used to inform sketching assessment measures and practices in sketching research literature?
3. What are the educational purposes and wider learning contexts of sketching assessment that exist in peer-reviewed sketching literature?

2 | LITERATURE REVIEW

2.1 | Sketching for engineering and design

This systematic review does not address computer models or technical diagrams. Likewise, it does not address engineering drawings as a means to communicate technical information of dimensions and scale for manufacturing (Setiadi, 2020) so much as abstract representations of concepts or ideas. Drawings are formal images that follow scale, dimensions, and symbols that convey technical information for the purpose of manufacturing (Hasenhütl, 2020); sketches, as we use the term here, are open-ended, abstract, conceptual sketches that are used early in the design process (Pei et al., 2010) and for idea generation and communication. Engineers can benefit from learning design and artistic approaches to sketching, as doing so supports the development of visualization skills, idea generation, and enhanced communication (de Vere et al., 2011). Design-based sketching methods for engineers can improve many aspects of the engineering process, including rendering and visualization, spatial reasoning, team communication, design creativity, visual communication, and technical drawing (Newton et al., 2018; Sorby, 2009). Sketching principles from visual arts support engineering graphics skills of projections, structures, three-dimensional (3D) assembly, and geometric principles (Y. Yang & Ren, 2022). Design sketches act as two-dimensional (2D) representations of 3D concepts from the designer's mental images to recreate and communicate its form and function, based on both perception and reality (Fish & Scrivener, 1990; Kim & Kim, 2009).

Sketching is beneficial for engineers as a professional skill. It facilitates team thinking when ideas are shared, discussed, and stored for future reference (Van der Lugt, 2005). It plays a role in multi-modal communication for engineering design teams, along with gestures, discussion, and other types of representations (Eris et al., 2014). As outward extensions of internal thought, sketches-in-progress support a dialogue between designers and their work as they are modified throughout the design process to fit evolving design ideas (Goldschmidt, 2003). During engineering design, sketching skills facilitate idea fluency, exploring the design space and novel idea generation (Bao et al., 2018). In the early stages of design, engineers use freehand sketching to explore possibilities when generating and modifying ideas, and later when refining design concepts (Buxton, 2010). Sketches are an important way of representing and coordinating design tasks (Atman et al., 2007). Freehand sketching is an informal way of representing multiple ideas during brainstorming (Lipson & Shpitalni, 2000). In addition to the physical activity of creating and revising a new image, sketching is a cognitive activity for designers to identify and relate specific features, to depict and re-interpret functional aspects, and to relate a design concept to larger goals (Bilda & Demirkan, 2003). Design teams can use *prescriptive sketches* for mapping out detailed plans, *thinking sketches* for drafting and modifying ideas, and *talking sketches* for working through ideas as a team (M. C. Yang, 2009). These sketches become more technical as design ideas are solidified to form prototypes.

Sketching provides engineers with a visual language to communicate the physical and functional properties of an object, along with its more conceptual and aesthetic features. An important purpose of sketching is information visualization, and it serves as a knowledge management tool for creating, sharing, and documenting collaboration (Pfister & Eppler, 2012). Sketches represent significant groups of conceptual information during design ideation that reflect designers' internal chunking cognition (Mao et al., 2020). Sketches act as external representations of internal models, knowledge structures, and processes that engineering teams can share, modify, and transform (Lille, 2013). Representational fluency is the ability to translate conceptual information within and across multiple representations, a skill that aids in problem solving (Moore et al., 2020). Sketching also gives engineers the tools and symbolic language to strategically represent design ideas and create new ones from imagination (Sung et al., 2019). In these ways, sketching supports design team processes of ideation, conceptual thinking, and brainstorming.

Digital sketching uses tablets and smart pens for freehand sketching (Evans et al., 2015). As a freehand sketching medium, digital sketching tools offer advantages over physical paper-and-pen materials while still supporting the perceptual and motor aspects of learning to sketch (Zhang & Ranscombe, 2021). Tablet sketching supports drawing layers, shading, rendering, and editing beyond pen-and-paper sketching while still affording the benefits of manual sketching over 3D modeling (Evans & Aldoy, 2016). Technology and software can support sketching assessment by translating pen-and-paper work into digital graphics and interpreting them with sketch recognition algorithms. Large classroom sizes are challenging for instructors to give personalized feedback, but intelligent software can guide students to master sketching at their own pace through artificial intelligence (AI)-based instruction (Valentine et al., 2012). With AI applied to engineering education contexts for adaptive and personalized learning, intelligent digital tutors have the potential to support sketching through more high-quality interactions (Ranscombe & Bissett-Johnson, 2017). Intelligent tutoring for digital sketching translates sketch recognition into instructional methods of personalized instruction, feedback, and guided practice for skill development (Williford, 2017). In this way, learning to sketch can be made more scalable and accessible with support from intelligent tutoring software. This systematic review examines freehand sketching broadly across both physical and digital media. As a subtopic of freehand sketching, digital sketch recognition applications are included in this review as they are used in engineering education.

2.2 | Sketching assessment

Assessment at the classroom level is necessary to evaluate sketching instruction for engineering education, but metrics and approaches to evaluate sketching can be diverse. We are interested in the approaches to sketching skill assessment in individual students and classrooms, so we focus on specific educational impacts of sketching assessment.

A variety of metrics can be used when relating sketching skills to design. In a summary of over 30 metrics in 14 research papers analyzing sketches across quantitative, qualitative, and mixed-methods design studies, Joshi and Summers (2012) collected metrics on 2D versus 3D, drawing/representation media, information content, motion indicators, proportion correctness, views, quantity, quality, variety, and novelty. Comparison of trends in objective versus subjective grading found that, whether qualitative or quantitative, objective criteria did not require inferences by judges, whereas subjective criteria were implicit and depended upon judges' interpretations to grade (Joshi & Summers, 2012). Inter-rater reliability was a way of showing agreement when inferences were required. Subjective grading also tended toward evaluating the quality of the sketch, such as to what degree or level a quality could be assessed. Joshi and Summers (2012) concluded that studies with similar research questions use different sketch metrics and that researchers often do not define the same metrics in the same ways.

When evaluating creative products such as art portfolios, instructors may assign scores to sketches, but the sketch features or students' skills being graded are unique to each case, making it a subjective process. In design and fine arts, grading sketch products such as sketchbooks or portfolio work often use comparative judgment or expert ratings of quality (Owen, 2020). For example, Clark's Drawing Abilities Test (1989) screened students with visual arts talent, using raters' holistic judgment of quality to assign a score of 1 to 10 to descriptive and imaginative drawing tasks. Cham and Yang (2005) also measured sketching skills with student performance on creative drawing tasks to measure mechanical recall, drawing facility, and novel visualization abilities as two mechanical engineering design experts holistically graded the sketches for structure, concept, operation, realism, proportions, and 3D accuracy. Tarricone and Newhouse (2017) investigated the reliability of comparative judgment for assessing portfolios of creative artifacts and process documents, first by experts and then by teachers, and found that comparative judgment grading produced greater reliability among teachers than analytical grading, although expertise or lack thereof was a key factor. In an overview of common holistic sketch grading methods, Peters (2020) identified five common strategies for assessing freehand sketching and drawing products: (i) group-sorting into three or more levels of quality, (ii) grading as an assignment by what learning objectives they meet in the overall course, (iii) quick scan holistic, intuitive grading from observation, (iv) comparison grading for improvement based on previous assignments, and (v) displaying all sketches in an exhibition hall and grading them together. All of these methods rely on decisions by experts to intuitively grade sketches according to their judgment against criteria.

Assessment of a sketch product may measure its more technical features. For example, Lau et al. (2009) counted annotations and representations within physical and digital design notebooks to illustrate longitudinal sketching trends during the design process. Annotations were grouped by dimensions, calculations, or multipurpose, while sketches were identified only as 2D or 3D. A study of spatial visualization learning for technical engineering drawing by Dragović et al. (2019) examined position, angle, and distance of lines in seven geometry tasks such as bisecting angles and finding points of convergence. Research has also used a combination of sketch and student measures for assessment. Sung et al. (2019) used both sketch-focused and student-focused assessment metrics for elementary students' electrical circuit design sketches, using a quality rubric evaluating conciseness, accuracy, and practicality of design sketches. The authors also coded think-aloud dialogue for cognitive design strategies. de Vere et al. (2011) also used both sketch quality metrics (perspective accuracy, line work quality, hierarchy, and inclusions of user interactions) and ideation metrics (quick conceptualization ability, idea diversity, innovation, and aesthetics) in a unit teaching industry-relevant sketching skills for product designers.

Sketching in engineering sits at the boundaries of design, engineering, and art, making many assessment methods from these disciplines potentially applicable. According to Rose (2005), sketching as a technical skill gives engineering students practice observing a subject and estimating its dimensions and measurements. As a cognitive process, sketching gives engineering students time to think about a subject's construction or circumstances and analyze its needs (Rose, 2005). Therefore, engineering sketching assessment should examine how sketching demonstrates both technical and cognitive skills. Owing to the variety of assessment approaches, metrics, and learning contexts for sketching, we wished to identify the commonalities and meaningfully highlight differences, especially in cross-disciplinary areas where sketching is taught. This systematic review is centered on engineering education but also examines literature in proximal disciplines to engineering to inform a richer understanding of sketching assessment.

3 | METHODS

This study follows the systematic literature review methodology outlined by Borrego et al. (2014). Our review process and decisions at each stage are shown in Figure 1. In the first phase, we defined the scope and research questions of the review, listed inclusion and exclusion criteria, selected databases, and developed search strings. In the second phase, we sorted papers first at the abstract stage and second at the full paper stage. In the third phase, we conducted two types of analysis to evaluate the papers' quality and to investigate their content. Borrego et al. (2014) describe several purposes for conducting systematic literature reviews in engineering education (p. 50): trace historical development; describe the

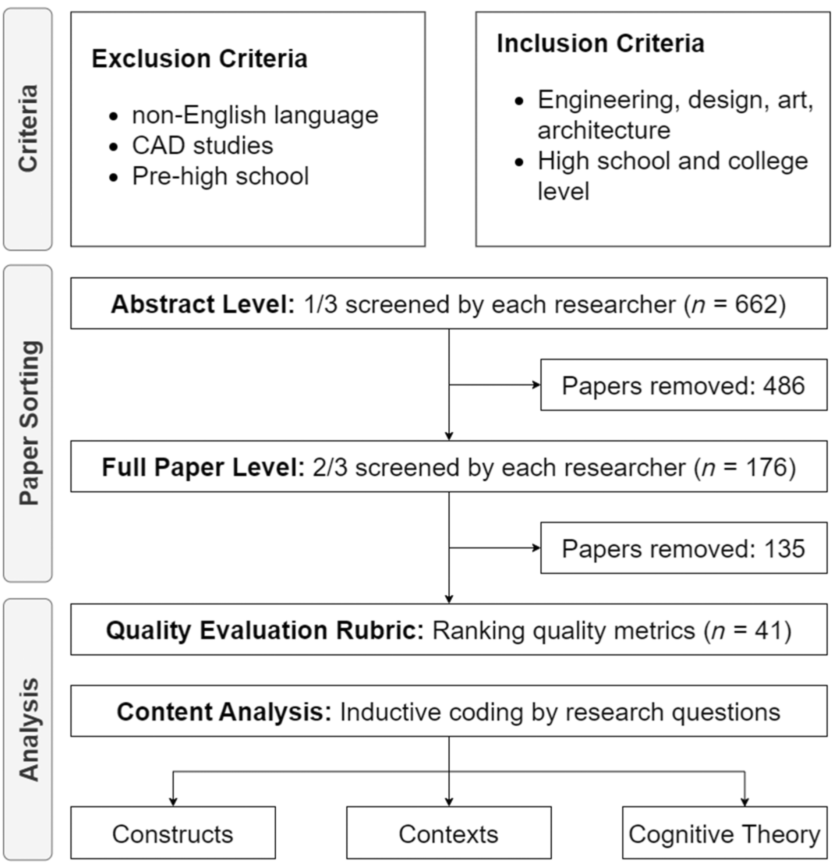

FIGURE 1 Systematic literature review decision process.

state of knowledge or practice; evaluate or develop theory; and identify opportunities for future research and innovations. The aim of this review was to understand what about sketching is being assessed, how and why sketch assessment is used, and whether any connection to underlying learning and cognition theories is being made.

3.1 | Inclusion and exclusion criteria

With the guidance of a professor of libraries who is skilled in systematic literature review, three researchers defined inclusion and exclusion criteria to reflect our research questions when screening papers:

- We included papers from engineering, design, art, and architecture education, as they all potentially include freehand sketching.
- We included peer-reviewed journals and conference papers, as peer review is an essential step in high-quality research.
- We excluded research on CAD software because it requires technical skills and experience distinct from those freehand sketching requires.
- We excluded studies of students below ninth grade.
- We excluded studies of technical drawings, such as drafting or free-body diagrams, because they are not freehand approaches.

3.2 | Database search

In total, we collected papers from six databases or sources. With consultation from a professor of libraries, we initially chose three databases that were most relevant to our research questions. Education Source represents the most extensive global collection of education literature and therefore is our primary source of literature. Engineering Village, containing the databases Compendex and Inspec, is the most comprehensive library of engineering papers globally and contains literature outside of education from professional journals. APA PsycINFO represents literature on formal assessment following psychometric methodology for development and validation. Databases such as ProQuest or Web of Science may also contain engineering literature but were less likely to include education or assessments, and therefore we did not search them.

We iteratively developed our search string containing 3–4 components to fully capture our research questions (see Table 1) following Borrego et al.'s (2014) framework. We included "draw*" as well as "sketch*" to include papers from art and design literature. The additional string (teach OR learn OR instruct*) was used to search Engineering Village for education papers. We then decided to broaden our search to include literature from computing and engineering conferences. This search had three components. First, we searched for papers in the comprehensive computing and information technology database of the Association of Computing Methodology (ACM). Second, we searched the American Society for Engineering Education Papers on Engineering Education Repository (ASEE PEER) conference

TABLE 1 Search strings by database accessed.

Database	Search strings
Engineering Village	(sketch* OR draw*) [Title] AND (skill OR abilit*) [Subject/Title/Abstract] AND (test OR assess* OR measure OR evaluat* OR instrument OR quiz) [Subject/Title/Abstract] AND (teach OR learn OR instruct) [Subject/Title/Abstract]
APA PsycINFO Education Source ACM Digital Library ASEE PEER	(sketch* OR draw*) [Title] AND (skill OR abilit*) [Subject/Title/Abstract] AND (test OR assess* OR measure OR evaluat* OR instrument OR quiz) [Subject/Title/Abstract]

proceedings. Finally, we used snowball sampling to collect individual papers from the references of papers found by the first round of data collection. We stored and shared downloaded papers in the reference manager Mendeley.

3.3 | Paper sorting

Using our inclusion and exclusion criteria, we reviewed two abstracts as a team to ensure consensus on applying the criteria. Each reviewer was then assigned one-third of the abstracts to review independently. We marked abstracts as (i) *Include* for full paper review as clear acceptance in later content analysis; (ii) *Full Read* for possible acceptance to thematic analysis after full paper review; (iii) *Exclude* for not matching our criteria, and (iv) *Discuss* the abstract to reach a consensus on inclusion or exclusion. We again sorted papers following inclusion and exclusion criteria for the full paper review stage. Each reviewer was assigned two-thirds of the papers, so that at least two reviewers reviewed each paper to ensure consensus. We marked full papers as (i) *Include* for acceptance to the content analysis and (ii) *Exclude* for removal as not matching our criteria. Of the excluded papers, we also marked the subgroups for later discussion.

3.4 | Quality evaluation rubric

A quality evaluation framework was also applied to the final paper dataset, in line with the recommendations of Borrego et al. (2014) for systematic literature reviews. A quality framework provides a ranking system to understand whether necessary research considerations were followed and reported in the studies. Systematic literature reviews from medical science research often include protocols for reporting quality, particularly regarding risk of bias within and across studies (Moher et al., 2009). Quality evaluation is highly subjective based on the research goals of the systematic review and the practices of the discipline in which it occurs. The Standards for Educational and Psychological Testing (AERA, APA, & NCME, 2014) highlight the responsibility of test developers to define and justify the validity of score interpretations for relevant subgroups (Standard 3.6, pp. 65–66). A second standard prevents inappropriate score use by specifying how test results should and should not be interpreted (Cluster 4, Standard 3.15, p. 70). We were interested in collecting metrics based on peer review as a standard of academic research, assessment validity and reliability evidence, and relevance to our three research questions of constructs and metrics, cognitive theory, and learning applications. Rankings from the quality evaluation are incorporated into the content analysis as extra information about how a study was conducted, giving additional insight into its reliability and trustworthiness.

3.5 | Content analysis

To analyze the final set of full papers from the systematic literature review, we used content analysis as outlined by Krippendorff (2013). This methodology addresses a problem, issue, or topic by examining available texts and presenting trends and current standards using evidence, evaluation, and judgment. It gives a name to phenomena, concepts, and dialogues and investigates institutional processes through an in-depth study of documents and codified practices (Krippendorff, 2013). It derives indices from studies while also critiquing their validity and reliability. While systematic literature review focuses primarily on the data collection process, content analysis is an approach for looking within and across studies to derive meaning (Krippendorff, 2013). Research questions may focus on the messages contained in texts or on the properties of the analyzed texts. Analytic coding may be used alongside qualitative investigation to synthesize literature by metadata and meaning. Quantitative content analysis as an interpretive methodology helped us to navigate the scope of sketching assessment literature by allowing us to describe the assessments in the final paper set in addition to the frequency with which codes appear.

We took steps to ensure trustworthiness, transparency, and validity in this review. Combining content analysis and systematic review, we ensured trustworthiness through reliable, replicable, and valid methods and interpretability of constructs (Krippendorff, 2013). We began with three broad research question categories related to (i) assessment constructs and metrics, (ii) purposes and applications of sketching assessment, and (iii) cognitive theory informing sketching assessment. We then developed codes within each category using clear definitions of the topics and categories we were searching for. Transparency is critical if processes are to be replicable. Search strategies, keywords, databases, and inclusion and exclusion criteria are therefore documented in detail according to systematic review. However, validity is also essential to ensure that conclusions and inferences reflect what exists in the data—that claims and assumptions are made from evidence and based on the consensus of raters (Kane, 1992). Three researchers inductively coded a sample of papers by identifying text describing assessment, organizing codes into themes within each category, and discussing with each other to maintain consensus. Discussion of themes and codes and agreement as to which should apply were an essential part of establishing the validity of definitions and codes to achieve inter-rater reliability of the remaining papers (Krippendorff, 2013). One researcher then coded the remaining papers using the codebook established through this process. This process meant we did not need to calculate inter-rater reliability during content analysis. After coding, we reported patterns of codes across engineering, design, and art papers to compare sketching skills assessment methods by discipline.

4 | RESULTS

4.1 | Abstract review

Using the search strings we selected, we collected and cataloged 250 papers from Engineering Village, 211 papers from Education Source, 102 papers from APA PsycInfo, 28 papers from ACM Digital Library, and 71 papers from ASEE Papers on Engineering Education Repository (see Table 2). The abstract review stage identified 102 duplicates and 376 papers that did not meet the criteria; 153 papers were included or advanced to full read and 31 papers required further discussion (see Table 3). Examples of reasons for reviewer discussion include reviewing assessments in early childhood education for potential relevance, uncertainty about subject or type of drawings being assessed, and uncertainty about what is assessed. The term "draw" overlapped with additional meanings and did not prove useful for collecting papers from art and design disciplines. Abstracts marked for full read most often included some type of sketching assessment but did not specify how sketches were assessed or how sketching was defined or measured. Of the 31 papers needing discussion, we removed 1 as a duplicate, included or advanced 15 to full read, and excluded 15.

From the excluded papers, we learned that the developmental psychology literature often used drawing as a measure for inferences about intelligence or creativity. We also found that many excluded studies were pre–post intervention studies that used spatial tests as the assessment to measure sketching's impact on spatial visualization or

TABLE 2 Papers collected by database.

Database	*N*
Engineering Village	250
Education Source	211
APA PsycINFO	102
ACM Digital Library	28
ASEE PEER	71
Snowball Sampling	9
Total	671

TABLE 3 Review decisions at abstract and full paper levels.

	Abstract	Full paper
Include	51	41
Full Read	110	–
Discuss	31	–
Exclude	377	127
Duplicates	102	8
Total	671	176

spatial skills development. Many excluded studies presented new computer tools for image recognition algorithms, while others presented drawing tasks that were not freehand sketches. Biological sketches, conceptual sketches, geometry and mathematics sketches, free-body diagrams, and data graphs were types of drawing or sketching that we excluded as different from freehand sketching. In some excluded studies, sketching constructs and metrics were either undefined, too ambiguous to code, or graded as correctly or incorrectly sketched, without assessing any skill.

Full paper review was then conducted with the remaining sample of papers (see Table 3). At this stage, papers were most often excluded for not assessing freehand sketching, for researching child development, for only assessing spatial visualization, for not clearly specifying assessment constructs and/or metrics, for only grading sketches as correctly or incorrectly sketched without assessing sketching skill, and for using surveys or self-reported measures after sketching instruction instead of skills assessment. We included four studies of elementary or middle school students as an exception to the exclusion criteria. In these four studies, elementary and middle school education either were one of many grade levels and skill levels of learners being examined, or sketching skill assessment was very well articulated and relevant for our review.

4.2 | Full paper review

The Appendix contains a table of the final paper dataset. Papers were published between 1965 and 2019, with most published since 2009 (see Figure 2). Education journals and conference papers represented disciplines including art education, engineering education, mathematics education, and gifted education. Non-education-focused journals and conferences included papers addressing freehand sketching in relation to engineering design graphics, mechanical engineering, computer science, AI, and many areas of design.

4.3 | Quality evaluation rubric

Frequency results of the quality evaluation rubric are shown in Table 4. All papers were from peer-reviewed journals or conference publications. They included 25 quantitative studies, 8 qualitative studies, and 8 mixed-methods studies. All papers defined sketching constructs, but only 19 papers included a description of specific assessment metrics. All but one paper included some level of detail on the learning or research context, suggesting that the one exception was not written from a learning research perspective. Evidence of fairness appeared in 17 papers, one of which (in Appendix,

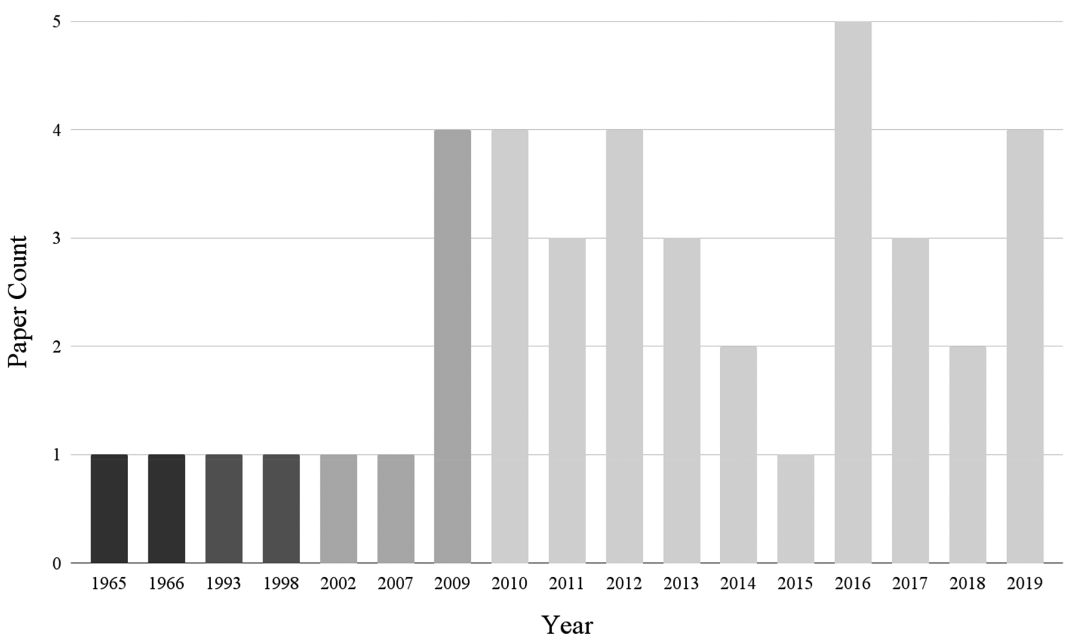

FIGURE 2 Final included papers and year by published decade.

TABLE 4 Quality evaluation rubric results.

Criteria	n
Is the reference a peer-reviewed journal or conference paper?	41
Are the research methods qualitative, quantitative, or mixed methods?	
Qualitative	8
Quantitative	25
Mixed methods	8
Are sketching constructs defined?	41
Are sketching metrics defined?	19
Is sketching cognition defined?	30
Does the assessment include a validity argument or evidence?	17
Does the assessment include fairness evidence?	17
Is there a wider learning application or context?	36

Barnhart & Walters, 2018) was entirely dedicated to investigating the effect of gender bias and stereotypes in industrial design on female designers' persistence and confidence, and the role of male-established norms when evaluating female students' design sketches. Another study articulated that art ability scores can be used for screening high-ability test takers into visual arts programs but should always be used alongside other measures of ability, and that scoring procedures differed for screening versus identification purposes (in Appendix, Clark, 1993). Arguments for valid score interpretation appeared in 17 papers, and most relied on multiple sources of evidence to construct a rationale for interpreting sketching skill. Measures of reliability or agreement, such as inter-rater reliability values of graders who scored sketches or internal consistency among test items, appeared in 12 studies.

4.4 | Content analysis

Codes for the first research category, namely assessment, are listed in Table 5. Classroom assessment included how sketching assessment was administered, most commonly through assigned sketching tasks or regular tests, but also through pedagogy such as using hands-on manipulatives, drawing free-body diagrams, or sectional views. The feedback and metrics codes had the greatest number of secondary codes. Forms of feedback included self-evaluation, peer evaluation, user feedback to sketching software, feedback from non-experts, and both formal and informal expert feedback. Studies that used computer feedback for assessment included sketch recognition algorithms that interpreted digital sketches. Computer feedback ($n = 49$), expert evaluation ($n = 33$), and sketch recognition ($n = 33$) were the most frequently coded types of feedback. A wide variety of metrics were used to assess sketches, most frequently line quality, accuracy, aesthetics, shape, assembly of lines or shapes, and perspective drawing. Some metrics were quantitative, such as the number of sketches, number of lines, and size/drawing area. Aesthetics metrics had a variety of definitions, such as detail, realism, style, expression, color, and professionalism. Scoring described whether value judgments were attached to sketch performance or products, with or without the use of a grading rubric to describe skill levels. Finally, test development processes and assessment of visual skills were described occasionally in the literature.

The codes in the second category, namely cognition, appear in Table 6. Perception was a prevalent code where students learned how to train their artistic eye by observing a sketch subject, focusing attention on specific aspects, disregarding illusions or hidden views, or thinking visually in space about shape and dimensions. Communication represented the purpose of sketching to support visual language and nonverbal thinking, commonly described as "thinking sketches." Think-aloud was an approach used in several studies to make sketch cognition observable by asking students to verbalize their thoughts and decisions during sketching. Analysis represented the ability to focus on and sketch specific parts of a whole subject, while synthesis demonstrated their ability to combine elements into complex compositions. Creativity described not only students' unique artistic ability to draw from their imagination but also the innovative thinking of designers to sketch creative solutions. This code was related to idea generation and problem solving, which often appeared in design and mathematics papers. Metacognition refers to students' critique and evaluation of their sketches, making decisions about what to change, planning out a sequence for sketching multiple

TABLE 5 Assessment code frequencies.

Parent code	Child code	*n*
Classroom assessment		41
	Free-body diagram	2
	Manipulatives	6
	Sectional views	2
	Sketching task	42
Feedback		66
	Computer feedback	49
	Sketch recognition	51
	Expert evaluation	33
	Expert feedback	6
	Formative feedback	1
	Non-expert evaluation	4
	Peer evaluation	1
	Self-evaluation	17
	User feedback	4
Metrics		124
	Accuracy	35
	Aesthetics	35
	Annotations	35
	Assembly	20
	Curve	7
	Drawing area	5
	Function	6
	Isometric drawing	3
	Line quality	39
	Motor skills	5
	Number	7
	Perspective drawing	39
	Projection	5
	Proportion	14
	Shading	16
	Shape	31
	Size	19
	Space	3
	Speed	10
	Stroke count	9
Scoring		74
	Rubric	14
Test development		6
Visual skill		17

elements, and using self-talk and self-monitoring during the sketching process. Representation was connected to communication regarding technical or replicative sketches containing detailed information. Spatial visualization and sketch memory were other adjacent cognitive abilities linked to sketching activity.

TABLE 6 Cognition code frequencies.

Parent code	Child code	n
Analysis		5
Communication		16
Creativity		15
Idea generation		9
Metacognition		9
Perception		23
	Hands-on	2
Problem solving		8
Representation		9
Sketch memory		2
Spatial visualization		3
Synthesis		8
	Expression	3
Think-aloud		8

The third set of codes, for context, are listed in Table 7. Design and engineering design were the most represented disciplines from the literature, followed by engineering, industrial design, architecture, product design, art school, civil engineering, and psychology. Participants in studies from the collected papers were primarily at the undergraduate level, but also from high school, graduate, and gifted education at the primary and secondary levels. Skill levels were most often beginner but included expert/experienced or professional. Of the studies that provided their region, North America, Asia, Europe, and the Middle East were represented. Technology-based sketching learning applications existed in online learning and instructional software. We also coded computer-based sketching technology used for assessment, including augmented or virtual reality and digital pens. The wider learning contexts where sketching took place included courses teaching CAD instruction for graphics and employing problem- or project-based learning (PBL) where students were approaching a design problem and active learning where students were engaged with sketching through hands-on methods such as sculpture. In some cases, sketching was part of homework assignments. Some studies also addressed classrooms in which students learned specific techniques of 2D orthographic views, perspective, isometric, or oblique sketching.

4.5 | Code patterns by discipline

In this study, we synthesized the methods, cognition, and learning contexts of sketching assessment in engineering education literature. We found that sketching is a prevalent topic in the literature across many disciplines, and only a small subset of our initially large dataset met our assessment criteria. Design (19 papers), engineering (10 papers), and art (4 papers) emerged as the three main disciplines in our dataset. The remaining 11 papers were unclassified. In this section, we discuss assessment, cognition, and context coding patterns within each discipline.

Assessment coding patterns were more similar between design and engineering than between design and art or engineering and art. In the design literature, expert feedback and computer feedback were more common than self or peer evaluation. Line quality, annotations, shape, perspective, and accuracy were the most coded metrics, with relatively few coded aesthetic words such as color, details, style, value, realism, or expression in design. Approximately half of the classroom assessment codes in design were sketching tasks. A small number of design assessment scoring codes also included rubrics. For the engineering papers, computer feedback appeared approximately as frequently as expert evaluation. Frequent engineering sketch assessment metrics were line quality; annotations; aesthetics such as style, value, context, and multiple views; and accuracy. A few engineering scoring codes also included a rubric. Classroom assessment themes in engineering were almost entirely sketching tasks. In the art papers, expert feedback, computer

TABLE 7 Context code frequencies.

Parent code	Child code	Tertiary code	*n*
Classroom learning			27
	Active learning		2
	CAD		8
	Homework		5
	PBL		12
Discipline			52
	Architecture		2
	Art		9
	Design		34
		Engineering design	21
		Industrial design	6
		Product design	5
	Education		2
	Engineering		18
		Civil engineering	2
	Psychology		1
Education level			37
	Gifted education		5
	Graduate		2
	High school		7
	Middle school		2
	Undergraduate		31
Online learning			12
	Instructional software		10
Region			28
	Asia		11
	Europe		2
	Middle East		1
	North America		15
Skill level			29
	Beginner		20
	Experienced		2
	Expert		3
	Professional		6
Technique			14
	Two-dimensional		6
	Isometric		4
	Oblique		4
	Perspective		18
Technology			4
	Augmented/virtual reality		2
	Digital pen		7

feedback, and non-graded formative expert evaluation were the most coded types of feedback. Metrics of aesthetics, shape, accuracy, size, shading, line quality, and annotations were the most frequently coded. Sketching tasks were coded in approximately half of the classroom assessment codes. Out of all scoring codes, Rubrics were coded somewhat frequently. Assessment was a major coding area for all disciplines, and we found expert input an important approach to assessment, along with reported scoring practices that indicate objectivity and ranking.

Cognition codes appeared most often in art literature, followed by design and engineering. In design papers, perception with hands-on interaction, synthesis, and creativity appeared most often. Metacognition, communication, and problem solving were also coded in design, but less frequently. In the engineering literature, perception was coded most often, followed by creativity, communication, idea generation, and representation. Synthesis, analysis, and spatial visualization appeared less frequently in engineering papers. Representation, communication, problem solving, and idea generation were prevalent in art literature, suggesting that fine art sketching has applied purposes in classroom tasks beyond learning how to represent the world. In contrast, creativity was coded only once in the art papers. From this cross-section, we can see that different types of cognition are emphasized depending on the goals of sketching, but that learning to perceive the subject and develop an artist's eye remains the most important type of sketch cognition.

Context showed an overlap in discipline codes, as a subset of papers contained codes in both design and art, and design and engineering. This is consistent with design's application to many types of problems and the use of design methods across disciplines. Design papers also included the disciplines of product design, engineering design, and industrial design. For education level, high school and undergraduate were coded in design papers, while middle school, undergraduate, and graduate education levels were coded in engineering papers. Gifted education, high school, and undergraduate education levels were coded in art papers. Design and engineering papers mentioned specific sketching techniques, with isometric and oblique sketching coded in engineering literature and perspective and 2D drawing coded in design and engineering. In contrast, art papers did not list specific techniques. Design and engineering papers also emphasized classroom learning more often than art to teach sketching, as design implemented PBL and CAD and engineering used PBL and homework. All three disciplines' papers reported the use of sketching technologies such as online learning and instructional software, with digital pens coded in both engineering and art papers.

4.6 | Results synthesis

For the first research question, *How is sketching ability assessed in engineering education literature?*, we found both general and specific metrics on a wide range of skills constituting sketching performance. Metrics were often not clearly defined in the literature, but the most commonly used metrics were shape, size, accuracy, line quality, perspective, and aesthetics. These metrics were most often quantitative, and scoring was frequently used to evaluate performance and compare levels, but rubrics to define evaluation criteria were not as common. Expert evaluators were an important part of the assessment process, whether through informal evaluation or formal feedback. In some cases, experts themselves contributed to establishing assessment metrics or scoring methods. In others, experts calculated inter-rater reliability during scoring. In several instances, experts judged the sketches based on their professional expertise as subject matter experts. Sometimes, expert advice was used to supplement computer feedback. Across all these roles, experts remained important for assessing work as shown by very frequent codes of expert evaluation, but not as frequently for formative feedback. Most studies used a scoring system for assessment even when a formal rubric was not present. Scoring was a way of quantifying sketching activity for comparing groups of students, assigning grades, linking sketching ability to other performance measures, ranking sketches, and showing pre–post improvement. Scoring was also qualitative to holistically indicate levels of ability or improvement. The McGown et al. (1998) taxonomy of sketches by levels of complexity appeared in the research methods or literature review of 10 papers (in Appendix, Yang & Cham, 2007; Westmoreland, et al., 2011; Srinivasan et al., 2016; Song & Agogino, 2004; Booth et al., 2016; Schmidt et al., 2012; Ruocco et al., 2009; Kudrowitz et al., 2019; Kwon & Kudrowitz et al., 2019) as a sketch-ranking approach. This framework provided a standardized way of classifying sketches to make holistic judgments about their quality. Given the need to disseminate effective sketching assessment tools to the engineering education community, such frameworks can be useful in research settings to evaluate sketching ability when graded skills and scoring procedures are clearly defined.

For the second research question, *What cognitive theories are used to justify assessment?*, we observed a wide range of interconnected cognitive skills supporting sketching learning. Perception, as the skill of seeing a sketch subject, was the most common sketching cognitive theory. This supports the idea that sketching is an internal process as much as a motor skill. Internal processes are made external in sketching through cognitive activities such as representation, communication, and thinking aloud. Analysis and synthesis are opposites, but both related to perception, as students focused on individual features of a complex sketch subject during analysis and combined elements to transform them into an artistic product during synthesis. Idea generation and creativity were both directly and indirectly assessed, and often used to justify the need for strong sketching abilities in engineers and designers. Metacognition was a cognitive ability with potential for classroom learning and feedback as students were actively reviewing their work and monitoring their progress. Each cognitive activity we found has been studied in engineering education and educational psychology, but in the context of sketching assessment, these theories may be studied in greater depth to support models of sketch cognition.

For the third research question, *What are the purposes of sketching assessment?*, we saw learning contexts across many fields and skill levels. Most studies concentrated on assessing sketching in the context of classroom learning, especially design problem studies or engineering computer graphics instruction. Sketching assessment was typically well incorporated into classroom practice, and assessment was used to measure learning improvements after classroom interventions. Sketching technologies were a notable aspect of sketch context, especially sketch recognition software. These studies often focused on drawing specific subjects, such as faces, and the computer's success in interpreting student drawings. They translated recognition into feedback, which instructed students on what they did and did not successfully draw. Other technologies, such as digital pens and instructional software, were examined for their usability when piloting new tools to facilitate sketching instruction and collect user feedback from students. A drawback of many sketch recognition papers is presenting and testing new software features and usability without clear application to learning. Most sketch recognition and computer feedback studies went beyond simple accuracy metrics and instead modeled a sketch-learning process that evaluated students' work step by step and gave input. In this way, sketch recognition studies were interested in student cognition, such as enhanced awareness of the drawing process, by analyzing complex drawing subjects and drawing elements one at a time, and evaluating their work based on detailed feedback.

5 | DISCUSSION

Our findings show that sketching skills assessment is a small part of the sketching literature, as most collected papers were not studies of freehand sketching, and most that were did not specify constructs and metrics. Defining and quantifying sketching skills is challenging, as many excluded studies graded based on correctness alone without examining skill. As constructs and metrics vary by discipline, the assessed sketching skills may change depending on its learning purpose, whether for creative expression, idea generation, or improving spatial visualization. Feedback was an essential element of sketching assessment, as many types of feedback were used, including formal expert review with evaluation criteria, informal expert feedback, often without grades attached, and peer review. Scoring and grading were key topics in the literature, even when constructs and metrics were not specific.

Learning how to perceive what is being sketched develops visual skills, which is essential for engineering sketching. Perception was the most referenced cognitive rationale for conducting sketching assessment. This indicates that students learn sketching from observing physical objects, rather than generating new images from their imagination. Studies also discussed communication and creativity as potential cognitive benefits of sketching, reflecting much of the existing conversation in engineering education and engineering design literature on the necessity of learning to sketch. If engineers are fluent in sketching as a natural part of thinking and visualization, this can contribute to their ability to communicate with teams and clients and their creativity when solving problems and generating ideas. Within the interdisciplinary sketching literature, we found that students learned and were assessed within the learning activity more often than with stand-alone tests or exercises. Although some studies were interested in comparing experts and beginners, most were assessing beginner skills, which can also make methods generalizable to other classrooms. Online learning contexts with instructional software and sketching technology represent new media for sketching assessment that researchers and instructors can pursue for scalable and personalized assessment.

Our findings have several implications for instructor practice. First, value was attached to assessment results for measuring progress or rating skills, which could be problematic if assessment criteria are not clear and fairness and validity evidence is not robust. Rubrics were also frequently paired with expert review, suggesting that detailed feedback is important when evaluating sketches. Assessment was primarily informal and well integrated with classroom practices, as opposed to relying on stand-alone instruments. Instructors can intentionally integrate assessment into homework, problems, and design projects to practice sketching. Second, idea generation, representation, metacognition, and problem solving are complex cognitive activities from design and engineering papers where students applied and monitored their sketching skills to accomplish goals. Fewer assessments explicitly incorporated these deeper cognitive strategies into their criteria. To assess engineering sketching skills, instructors should develop assignments or exercises that help students use challenging cognitive skills during sketching. If instructors are aware of the cognitive strategies used during sketching and the applications of sketching toward challenging cognitive activity, they can tailor assessment questions to support them in addition to sketch quality or performance. Third, classroom learning was typically where sketching assessment was used in active learning, CAD lessons, homework assignments, and PBL at the undergraduate level. Because assessment is often informal and driven by instructor feedback, such student-centered approaches are also useful for investigating sketching learning. Authentic assessment will incorporate sketching into the tasks and objectives of classroom learning for students to be motivated to sketch and for instructors to have better evidence of their abilities.

6 | LIMITATIONS

Although our goal was to enrich the discussion of engineering sketching through proximal design and art literature, our results may have been more applicable to engineering if we confined our content analysis to engineering papers only. As a qualitative inquiry, this study is meant to be a rich, detailed look into a specific topic to understand methods and decisions. Results are intended to inform engineering education instructors and researchers of sketching teaching and assessment strategies by describing who has implemented them and how while determining whether high-quality test development, test administration, and score reporting methods were used.

Our choices of databases and search strings were intended to broadly review the literature on sketching assessment; however, there may be additional relevant papers outside of the databases used in this study. Sketching assessment literature is not housed in one specific field, and thus we consulted with several experts of different backgrounds to determine our search strategy. We consulted with a professor of libraries with experience in systematic reviews about how to structure our research questions and strategically collect literature to answer them. Their expertise helped mitigate the risk of gaps in our literature search. We included only English language papers, which may have excluded significant areas of progress toward our research questions from authors who write in other languages. Future research should consider reviewing publications from non-English-language journals by including researchers who are proficient in other languages. Finally, our choice to exclude gray literature and non-peer-reviewed journals may have created selection bias. Expanding our selection criteria to these papers could enhance our knowledge of sketching assessment methods in engineering.

Although global region and education level were reported in some studies, we did not code for gender or racial and ethnic demographics of students in each study. Nearly half of collected studies reported fairness evidence according to our quality evaluation rubric, and although these studies often addressed gender bias and testing by levels of skill, only one directly discussed implicit bias and fairness in testing practices and assessment (in Appendix, Barnhart & Walters, 2018). Demographic factors influence students' classroom learning and assessment experiences; therefore, future work may investigate assessment practices in more detail while taking racial and gender bias issues such as lack of representative sampling, generalizing results, or biased test language and administration through the perspective of more detailed demographics.

7 | CONCLUSIONS

Sketching is an important skill for engineers and engineering designers that is challenging to assess. The purpose of this study was to promote high-quality assessment of engineering sketching by systematically reviewing the engineering education literature for constructs, cognition, and contexts. The reviewed literature shows a need for validity and reliability evidence through clear assessment definitions. It also illustrates the importance of cognitive theories such as visual thinking and communication for understanding how and why students sketch. Authentic assessment contexts incorporated sketching into engineering design projects and CAD instruction. Opportunities exist for assessment experts in engineering education, design education, and related fields to improve sketching assessment. New instruments can be developed that align with engineering design and graphics learning goals while allowing students to practice sketching. Validation of existing assessments can provide evidence for use with many student populations. Ongoing improvement of sketching assessment methods and studies of its use in engineering classrooms will contribute to promoting sketching as a valuable engineering skill.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX

FINAL REVIEWED ARTICLES

No.	Citation	Codes	References	Year
1	Nagai, T., Kayama, M., & Itoh, K. (2014). A drawing learning support system based on the drawing process model. *Interactive Technology and Smart Education, 11*(2), 146–164. https://doi.org/10.1108/itse-05-2012-0016	22	65	2014
2	Luh, D. B., & Chen, S. N. (2013). A novel CAI system for space conceptualization training in perspective sketching. *International Journal of Technology and Design Education, 23*(1), 147–160. https://doi.org/10.1007/s10798-011-9171-7	18	46	2013
3	Widder, M., Berman, A., & Koichu, B. (2019). An a priori measure of visual difficulty of 2-D sketches depicting 3-D objects. *Journal for Research in Mathematics Education, 50*(5), 489–582. https://doi.org/10.5951/jresmatheduc.50.5.0489	15	50	2019
4	Yang, M. C., & Cham, J. G. (2007). An analysis of sketching skill and its role in early stage engineering design. *Journal of Mechanical Design, 129*(5), 476–482. ASME. https://doi.org/10.1115/1.2712214	28	83	2007
5	Westmoreland, S., Ruocco, A., & Schmidt, L. (2011). Analysis of capstone design reports: Visual representations. *Journal of Mechanical Design, 133*(5). https://doi.org/10.1115/1.4004015	16	40	2011
6	Czapka, J., Moeinzadeh, M., & Leake, J. (2002, June). Application of rapid prototyping technology to improve spatial visualization. In *2002 ASEE Annual Conference and Exposition Proceedings* (pp. 7–211). https://doi.org/10.18260/1-2--10538	12	21	2002
7	Hammond, T., Prasad, M., & Dixon, D. (2010, June). Art 101: Learning to draw through sketch recognition. In *International Symposium on Smart Graphics* (pp. 277–280). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-13544-6_30	7	22	2010
8	Akasah, Z. A., & Alias, M. (2010). Bridging the spatial visualisation skills gap through engineering drawing using the whole-to-parts approach. *Australasian Journal of Engineering Education, 16*(1), 81–86. https://doi.org/10.1080/22054952.2010.11464037	21	38	2010
9	Jeong, S. (2019). Case study: Effectiveness of a sketch learning model for engineering students. *Journal of Mechanical Science and Technology, 33*(12), 5721–5730. https://doi.org/10.1007/s12206-019-1115-2	29	111	2019
10	Nagai, T., & Kayama, M. (2013). Collaborative drawing process viewer for enhancing self-drawing reviewing awareness. 2013 International Conference on Interactive Collaborative Learning (ICL). https://doi.org/10.1109/icl.2013.6644551	11	28	2013
11	Keshavabhotla, S., Williford, B., Kumar, S., Hilton, E., Taele, P., Li, W., ... & Hammond, T. (2017, July). Conquering the cube: learning to sketch primitives in perspective with an intelligent tutoring system. In *Proceedings of the Symposium on Sketch-Based Interfaces and Modeling* (pp. 1–11). https://doi.org/10.1145/3092907.3092911	25	98	2017
12	Hilton, E., Blake, W., Wayne, L., Erin, M., Tracy, H., & Julie, L. (2016). Consistently Evaluating Sketching Ability in Engineering Curriculum. In *DS 86: Proceedings of The Fourth International Conference on Design Creativity*, Georgia Institute of Technology, Atlanta, GA, USA.	23	85	2016

No.	Citation	Codes	References	Year
13	Inadome, T., Soga, M., & Hirokazu, T. (2012). Development of sketch learning support environment using augmented reality and step-by-step drawing. In *Workshop Proceedings of the 20th International Conference on Computers in Education (ICCE)*, 482–490.	19	59	2012
14	Chan, D. W. (2009). Drawing abilities of Chinese gifted students in Hong Kong: Prediction of expert judgments by self-report responses and spatial tests. *Roeper Review, 31*(3), 185–194. https://doi.org/10.1080/02783190902994084	15	33	2009
15	Putro, R. T. T. (2019, July). Drawing as a basic ability of design students in thinking visual and understanding of form logic. In *2019 16th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)* (pp. 450–453). IEEE. https://doi.org/10.1109/ecti-con47248.2019.8955203	18	40	2019
16	Rose, S. E., & Jolley, R. P. (2016). Drawing development in mainstream and Waldorf Steiner schools revisited. *Psychology of Aesthetics, Creativity, and the Arts, 10*(4), 447–457. https://doi.org/10.1037/aca0000070	24	83	2016
17	Carlson, J. A. (1966). Effect of instructions and perspective-drawing ability on perceptual constancies and geometrical illusions. *Journal of Experimental Psychology, 72*(6), 874–879. https://doi.org/10.1037/h0023862	17	23	1966
18	Hilton, E. C., Linsey, J. S., Paige, M. A., Williford, B., Li, W., & Hammond, T. A. (2017, June). Board# 52: Engineering drawing for the next generation: Students gaining additional skills in the same timeframe. In *2017 ASEE Annual Conference & Exposition Proceedings*. https://doi.org/10.18260/1-2--27874	26	37	2017
19	Lane, D. & Seery, N. (2011, June). Examining the development of sketch thinking and behavior. In *2011 ASEE Annual Conference & Exposition Proceedings*. https://doi.org/10.18260/1-2--17944	13	17	2011
20	Lane, D. & Seery, N. (2011). Freehand sketching as a catalyst for developing concept driven competencies. *Engineering Design Graphics Journal, 75*(1), 2–25. https://doi.org/10.18260/1-2--16391	26	61	2010
21	Marklin Jr, R. W., Goldberg, J. R., & Nagurka, M. L. (2013). Freehand sketching for engineers: A pilot study. *2013 ASEE Annual Conference & Exposition Proceedings*. https://doi.org/10.18260/1-2--19630	23	53	2013
22	Ding, S. (2011). Freshmen's drawing abilities with multi-media: an analysis of portfolios with grading rubrics. In 2011 *ASEE Annual Conference & Exposition Proceedings*. https://doi.org/10.18260/1-2--18009	19	43	2011
23	Cummmings, D., Vides, F., & Hammond, T. (2012, June). I do not believe my eyes! Geometric sketch recognition for a computer art tutorial. In *Proceedings of the International Symposium on Sketch-Based Interfaces and Modeling* (pp. 97–106).	16	36	2012
24	Srinivasan, A., Smith, J. D., & Bairaktarova, D. (2016, August). Identifying freehand sectional view technical drawing activities in engineering design graphics course to enhance spatial skills of engineering students. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 3). American Society of Mechanical Engineers. https://doi.org/10.1115/detc2016-60079	17	27	2016
25	Song, S., & Agogino, A. M. (2004, January). Insights on designers' sketching activities in new product design teams. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 46,962, pp. 351–360). https://doi.org/10.1115/detc2004-57474	25	57	2014
26	Booth, J. W., Taborda, E. A., Ramani, K., & Reid, T. (2016). Interventions for teaching sketching skills and reducing inhibition for novice engineering designers. *Design Studies, 43*, 1–23. https://doi.org/10.1016/j.destud.2015.11.002	19	53	2016
27	Yang, C. Y., Hu, Y., Chen, Y. Y., Yeh, L. J., Zou, E. W., & Huang, Y. Z. (2016). Is Spatial ability improved? Creative sketch training for product design students. *44th Annual Conference of the European Society for Engineering Education—Engineering Education on Top of the World: Industry-University Cooperation, SEFI 2016*.	20	38	2016

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28	Hammond, T., Kumar, S. P. A., Runyon, M., Cherian, J., Williford, B., Keshavabhotla, S., ... & Linsey, J. (2018). It's not just about accuracy: Metrics that matter when modeling expert sketching ability. *ACM Transactions on Interactive Intelligent Systems (TiiS), 8*(3), 1–47. https://doi.org/10.1145/3181673	31	100	2018
29	Clark, G. A. (1993). Judging children's drawings as measures of art abilities. *Studies in Art Education, 34*(2), 72–81. https://doi.org/10.2307/1320444	25	43	1993
30	Chan, D. W., Chan, L., & Chau, A. (2009). Judging drawing abilities of Hong Kong Chinese gifted students: Could nonexperts make expert-like judgments? *Gifted Child Quarterly, 53*(1), 15–24. https://doi.org/10.1177/0016986208326555	25	63	2009
31	Schmidt, L. C., Hernandez, N. V., & Ruocco, A. L. (2012). Research on encouraging sketching in engineering design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 26*(3), 303–315. https://doi.org/10.1017/s0890060412000169	31	92	2012
32	Chamberlain, R., McManus, C., Brunswick, N., Rankin, Q., & Riley, H. (2015). Scratching the surface: Practice, personality, approaches to learning, and the acquisition of high-level representational drawing ability. *Psychology of Aesthetics, Creativity, and the Arts, 9*(4), 451. https://doi.org/10.1037/aca0000011	8	32	2015
33	Soga, M., Fukuda, T., & Taki, H. (2009, September). Sketch learning environment for human body figure by imitative drawing. In *International Conference on Knowledge-Based and Intelligent Information and Engineering Systems* (pp. 599–606). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-04592-9_74	21	55	2009
34	Ruocco, A., Westmoreland, S., & Schmidt, L. C. (2009, January). Sketching in design: easily influencing behavior. In *ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 8, pp. 1249–1256). https://doi.org/10.1115/detc2009-87503	18	60	2009
35	Williford, B. (2017, June). Sketchtivity: Improving creativity by learning sketching with an intelligent tutoring system. In *Proceedings of the 2017 ACM SIGCHI Conference on Creativity and Cognition* (pp. 477–483). https://doi.org/10.1145/3059454.3078695	27	50	2017
36	Kensler, G. L. (1965). The effects of perceptual training and modes of perceiving upon individual differences in ability to learn perspective drawing. *Studies in Art Education, 7*(1), 34–41. https://doi.org/10.2307/1320045	9	27	1965
37	Barnhart, B. R., & Walters, K. K. (2018). The hot industrial design sketch: Perpetuating the dominance of the male industrial designer. In *DS 93: Proceedings of the 20th International Conference on Engineering and Product Design Education (E&PDE 2018)*, Dyson School of Engineering, Imperial College, London. 6th–7th September 2018.	19	37	2018
38	Kudrowitz, B., Te, P., & Wallace, D. (2012). The influence of sketch quality on perception of product-idea creativity. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 26*(3), 267–279. https://doi.org/10.1017/s0890060412000145	31	133	2012
39	Kwon, J., & Kudrowitz, B. (2019, August). The sketch quality bias: Evaluating descriptions of product ideas with and without visuals. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 7, p. V007T06A005). https://doi.org/10.1115/detc2019-97232	6	10	2019
40	McGown, A., Green, G., & Rodgers, P. A. (1998). Visible ideas: Information patterns of conceptual sketch activity. *Design Studies, 19*(4), 431–453. https://doi.org/10.1016/s0142-694x(98)00013-1	27	76	1998
41	Soygenis, S., Soygenis, M., & Erktin, E. (2010). Writing as a tool in teaching sketching: Implications for architectural design education. *International Journal of Art & Design Education, 29*(3), 283–293. https://doi.org/10.1111/j.1476-8070.2010.01646.x	25	66	2010