Assessment in the Service of Learning: An Example from AP® Art and Design

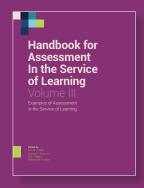
Rebecca Stone-Danahy, David S. Escoffery, Natalya Tabony, and Trevor Packer

UMassAmherst

University Libraries

Series Editors:

Edmund W. Gordon, Stephen G. Sireci, Eleanor Armour-Thomas, Eva L. Baker, Howard T. Everson, & Eric M. Tucker







© 2025 by Rebecca Stone-Danahy, David S. Escoffery, Natalya Tabony, and Trevor Packer

The Open Access version of this chapter is licensed under a Creative Commons Attribution—NonCommercial—NoDerivatives 4.0 International License (CC-BY-NC-ND 4.0).

ISBN: 978-1-945764-33-2

Suggested Citation:

Stone-Danahy, R., Escoffery, D. S., Tabony, N., & Packer, T. (2025). Assessment in the service of learning: An example from AP® Art and Design. In E. M. Tucker, E. L. Baker, H. T. Everson, & E. W. Gordon (Eds.), Handbook for assessment in the service of learning, Volume III: Examples of assessment in the service of learning. University of Massachusetts Amherst Libraries.

Assessment in the Service of Learning: An Example from AP® Art and Design

Rebecca Stone-Danahy, David S. Escoffery, Natalya Tabony, and Trevor Packer

With its focus on providing support materials for teachers and students that allow opportunities for real time feedback, the 2019 redesign of Advanced Placement (AP®) courses solidified the AP Program's commitment to the Assessment in the Service of Learning (AISL) ideals. AP Art and Design offers a model for the ways in which assessments can support the process of learning. The Art and Design course and assessment both drive student motivation, engage students in some way, and promote metacognitive skills. This chapter examines the structure of the AP Art and Design portfolio assessment along with the support offered to teachers and students, demonstrating how this program models the process-focused elements of AISL. Because the portfolio requires students to conduct an inquiry emphasizing process over product, AP Art and Design provides inherent motivation for students, keeps them engaged, and encourages metacognition. These factors make this assessment a prime example of AISL.

Prior to 2012, the Advanced Placement Program (AP®) provided, in essence, three components to participating educators and students. The original component, administered by the College Board on behalf of colleges and universities nationwide since 1955, was the summative AP Exam, written and scored not by the students' own teachers but by committees of college professors and expert high school instructors. Second, there was a "Course Description" booklet, which contained a short outline of topics typically taught in the corresponding introductory college courses. Finally, the AP Program partnered with professional development centers to provide professional learning workshops, primarily focused on familiarizing teachers with exam details, scoring standards and rubrics, and techniques for teaching advanced topics.

In 2002, the National Research Council and the National Science Foundation issued *Learning and Understanding*, a report that indicated that the primary goal of AP and other advanced educational programs should be to help students develop a deep understanding of the organizing concepts and principles in all disciplines, and accordingly, curricula should focus on a reasonable number of concepts.¹

In the decade that followed, College Board convened cognitive scientists and experts in each discipline, and from 2012, began implementing sweeping changes across the suite of 35 AP courses and exams, such that by Fall 2019, each AP course was redesigned, and anchored in a short list of transferable disciplinary skills that would now be the focus of each exam question. These skills became the spine of each AP course, recursively embedded within a finite body of content that would serve as a transparent compact with AP teachers about the full scope of content that could appear on an AP Exam.²

In short, this redesign of the 35 AP courses required a willingness for the sponsoring organization, College Board, to step away from an all-inclusive approach to course and exam topics—an approach that reflected the wide variation in content selected by the thousands of faculty and adjuncts who teach the college courses from which AP scores exempt students. Instead, the AP Program developed a transparent scope and sequence for each AP course, one informed as much by cognitive science researchers as by subject-matter experts in each field.

¹ Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools, Gollub, Jerry P., Bertenthal, Meryl W., Labov, Jay B., and Curtis, Philip C., Eds. National Academy Press, 2002.

² Drew, Christopher, "Rethinking Advanced Placement," New York Times, January 11, 2011.

This change required delineating content formerly eligible for inclusion, as off-limits, and outside the scope of the AP Exam. Because there is no perfect consistency in the topics valued by the approximately 4,000 colleges and universities that utilized AP scores to place students out of introductory courses on their campuses, the AP Program incurred some degree of risk that these changes would alienate a subset of faculty whose favored topics were not included on the AP Exam. To minimize that risk, the AP Program conducted extensive analyses of syllabi from a range of institutions receiving AP scores, generated a comprehensive list of all topics appearing in college syllabi, and asked faculty to rate each topic's essentiality as a prerequisite for successful further study of the discipline on campus. Topics were then removed if they did not have high average ratings as essential foundational content. In parallel, the AP Program partnered with faculty and AP teachers to conduct exam timing analyses with the goal being to determine an appropriate amount of exam content ensuring adequate instructional focus on the recursive, transferable discipline skills.

Another significant improvement made possible because of the redesign of AP's focused course topic delineation is the design and delivery of free formative course assessments for all AP students. In the past, students and teachers had no way to check progress and calibrate learning and performance to an external benchmark, until they received their summative AP Exam scores each July—too late to make use of such information for that year's population of learners. The AP Program released AP Classroom at the start of the 2019 school year in conjunction with the 35 redesigned AP subjects. For each topic in every AP course, the AP Classroom platform provides daily instructional videos from a racially diverse group of expert AP teachers, daily formative practice questions teachers can assign before class, and an associated student data dashboard for instructors. The instructor dashboard provides teachers the opportunity to focus their instruction on correcting student learning misunderstandings, rather than dedicating precious instructional time to content or skills that students are already demonstrating well.

Accordingly, AP Classroom builds on the redesign of AP Exams to provide learners and their teachers with real-time feedback on topics they've mastered, skills they're developing, and how to focus further practice where the need is greatest. As a result, the usage levels are high, as is teacher satisfaction. In the 2022–23 academic year, the students taking AP classes watched a total of 66 million instructional videos and took 45 million formative assessments, generating an unprecedented amount of

direct and relevant instructional feedback for themselves and their AP teachers. Over 80% of AP teachers use AP Classroom resources, and nine out of ten teachers report it helps prepare for the exam and learn course content³.

The free AP Classroom resources, anchored in the redesigned exams and course frameworks, now enable a cycle of teaching and learning supports that connect formative assessment data to instruction and learning, let alone preparation for the summative AP Exam, as Figure 1 depicts:

Figure 1.



- Plan
 Unit Guides
 Professional Learning Videos
- Teach
 AP Daily Videos
 Course-Specific Resources and Activities
- Practice
 Topic Questions
 Question Bank
- 4. Assess and Check for Understanding Progress Checks Question Bank
- 5. Get and Give Feedback Individual Assignment Feedback All Assignment Report Progress Check Report Content & Skills Performance Report
- 6. Review and Prepare
 Question Bank
 Practice Exams
 AP Daily Review Videos

Incorporating Projects and Portfolios into AP Assessments

AP Exams have traditionally been defined by a single, three-hour examination at the end of a course, determining whether a student earns a qualifying score for college credit or placement. However, this approach has begun to shift with the introduction of performance tasks and portfolios as integral components of the AP assessment. As of 2024, these assessment models are employed in seven courses, covering approximately 400,000 exams. While AP Art and Design has utilized portfolio development for decades, this concept has more recently been adopted in

courses like AP Seminar and AP Computer Science Principles (CSP), among others. This shift reflects an organizational belief that performance tasks allow for deeper instruction and learning, provide more authentic assessments of skills, and make learning more engaging and relevant for students. AP's existing project-based assessment shows evidence of improved student performance and strong demand from both teachers and students for incorporating such projects into AP courses and exams. However, while projects have demonstrated their value and addressed community needs, challenges and open questions remain about how best to implement them in the AP Program.

Benefits of Performance Tasks

The introduction of performance tasks in AP assessments has yielded several promising outcomes. For one, students in these courses tend to have more success on the assessment, with students of similar levels of academic preparation being more likely to earn qualifying scores than in other AP courses and with high success rates among Black, Hispanic, and first-generation students. Additionally, courses with performance tasks like AP Seminar and AP CSP contribute to strong student performance not only on the AP Exams themselves but also in subsequent coursework and college. For example, students who take AP Seminar tend to earn higher first-year GPAs and have better retention rates in college than students who do not take APs⁴. Similarly, AP CSP often serves as the first AP STEM experience for many underrepresented students, and those who take it are more likely to pursue further studies in computer science and related fields⁵.

Challenges and Open Questions

Despite these successes, challenges and open questions remain as AP continues to incorporate performance tasks into AP assessments. One of the main challenges is ensuring the security, validity, and consistency of these assessments—AP's core value proposition. Performance tasks, by their very nature, are more difficult to standardize than traditional exams. This challenge is compounded by the introduction of generative AI tools like ChatGPT, which raises new questions about ensuring authenticity.

⁴ Sanja Jagesic, Maureen Ewing, Jing Feng and Jeff Wyatt, "AP Capstone™ Participation, High School Learning, and College Outcomes: Early Evidence," College Board (2020).

⁵ Jeff Wyatt, Jing Feng, and Maureen Ewing, "AP Computer Science Principles and the STEM and Computer Science Pipelines," College Board (2020).

In the 2022–2023 school year, when tools like ChatGPT and DALL-E became widely available, AP initially attempted to enforce a ban on AI use in performance tasks. However, it became clear that this approach was neither practical nor beneficial. Instead, College Board is in the process of shifting over time to a policy of responsible integration, starting with AP Seminar and AP Computer Science Principles, allowing students to use AI tools in ways that support their learning while still ensuring that they demonstrate mastery of the material. Even with new policies in place, there are likely to be further issues to resolve as students and teachers learn more about both the benefits and shortcomings of generative AI tools.

Another challenge is the relatively low submission rates among Black and Hispanic students in courses that include performance tasks. Understanding the reasons behind these disparities is critical, as is finding ways to support all students in completing these tasks. This might involve rethinking guidance on how the tasks are administered, changing the performance task format or providing additional resources to help students succeed.

Building and scoring effective performance tasks and instructional resources requires significant resources and expertise. We are still in the process of developing archetypes for these tasks, balancing the need for valid assessment with the goal of providing space for student choice and creativity.

AP and Assessment in the Service of Learning

The literature on assessment in the service of learning highlights a number of different ways in which assessments can move beyond measurement and serve to enhance or improve learning. Whether it is by modeling expectations for test-takers, providing key insights to teachers, or establishing markers of progress, assessments can be used to improve learning outcomes. Of particular interest to assessment design is the way in which assessments can support the process of learning. This can be done by creating assessments that drive student motivation, engage students in some way, and promote metacognitive skills. In the areas of motivation and engagement, assessments can do things like providing "meaningful referents...that complement the previously existing cognitive frameworks of the student" (Qualls, 1998, p. 298). When students recognize themselves in the material presented on the assessment, they are more likely to be engaged and motivated to perform well. Encouraging metacognition, or a reflection on one's own thinking, means creating an assessment that encourages test-takers' "monitoring their own

understanding, predicting their performance, deciding what else they need to know, organizing and reorganizing ideas...[to] help them advance their understanding" (Earl, 2006, p. 4).

With its focus on providing support materials for teachers and students that allow opportunities for real time feedback, the redesign of AP courses that was completed in 2019 solidified the AP Program's commitment to the ideals of Assessment in the Service of Learning. And the shift toward performance tasks moves the needle even further. Of course, AP has had a model for this approach to assessment since 1972. AP Art and Design as a program has always modeled these process-related aspects of assessment in the service of learning, and with its own redesign, it now has additional factors that can motivate test-takers, support engagement, and encourage metacognition. Before we examine how these ideas play out in the redesigned course and portfolio assessment, however, we should provide some basic details about AP Art and Design, its history and its current program structure.

Art and Design: Pioneering Project Based Assessment in AP

In 1972, College Board pioneered standardized student portfolio submissions and assessment through AP Studio Art. Since then, participating high school students have had the opportunity to gain college credit or advanced placement in drawing, 2-D design, and 3-D design by achieving a passing score of 3 or above (on a scale of 1–5). As part of the AP Program's intentional course redesign focus, AP Studio Art was reimagined and became AP Art and Design in 2019. The revised course includes an increased focus on student inquiry to guide art-making through the Sustained Investigation portfolio component. In the Sustained Investigation, students answer two writing prompts:

- 1. Identify the inquiry that guided your sustained investigation.
- 2. Describe ways your sustained investigation developed through practice, experimentation, and revision.

The 2023 AP Art and Design *Course and Exam Description* (CED) defines a sustained investigation as "an inquiry-based and in-depth study of materials, processes, and ideas over time" (p. 43). In this portfolio component, students are encouraged to discover, explore, question, reimagine, practice, experiment, and

revise to demonstrate synthesis of materials, processes, and ideas. Students develop their inquiry based on personal experiences to create unique and original artworks. "Experiences can be documented by recording observations and perceptions related to an experience" (p.14) using "any materials, processes, and ideas as long as the work is the student's original creation" (p. 35). Thus, students are free to choose ideas, materials, and processes that are the most meaningful and personal to them (Escoffery et al., 2025). During the annual AP Art and Design exam assessment, readers (raters) often note that the most exciting and engaging portfolios to score are those derived from student passions, personal lives, and their art-making discoveries.

When assessing the sustained investigation portfolio component, readers use an analytic rubric to measure four art-making practices (See Appendix A):

- 1. guiding inquiry,
- 2. practice, experimentation, and revision in art-making,
- 3. synthesis of materials, processes, and ideas in art-making, and
- 4. portfolio skills.

Each Sustained Investigation analytic rubric row contains decision rules defining how a rater can apply a score of 1-3 to best award student achievement. In this portfolio component (worth 60% of the overall exam score), students demonstrate their thinking through art-making in writing and digitally submitted images and works (e.g., sketchbook pages, mood boards, mindmaps, experimental or process images, and final artworks). For example, in Figure 2, Daniel Stordahl, whose portfolio was featured in the 2024 AP Art and Design Exhibit (Stordahl, 2025), shares a digital image composite demonstrating the drawing process he used to tell the "story of young Julius Caesar's capture by pirates in 75 BC and his vow to return and destroy them" (para. 2). The written evidence accompanying his process work elucidates material choices and conceptual and physical process(es). Daniel describes his materials as "Paper, pencil, Adobe Fresco, iPad" while his processes include "Compose sketches, plan color/light, block shapes in vectors, render shadows/gradients, cinema border" (Stordahl, 2025, para. 2). By including part of his finished artwork in this process work, we understand the progression and choices made from inception to completion.

Figure 2.



Note. From Caesar Departs from Rome, by D. Stordahl (2025), 2024 AP Art and Design Exhibit (https://apartanddesign.collegeboard.org/2024-student07).

© 2025 D. Stordahl. Reprinted with permission.

In this image, the process writing informs the viewer's interpretation and when paired with Stordahl's inquiry statement (written evidence), the investigation into the relationship of exploring *The Revenge of Julius Caesar* through cinematic techniques to tell a story and convey emotion in a single shot is evident:

Throughout every step, I was intentional about contributing to the bigger picture of the story. For example, in "Caesar Departs from Rome," I wanted viewers to feel the power and glory of Rome, represented by the sunlit city in the background. At the same time, I positioned Julius Caesar venturing toward a cloud-covered area, symbolizing the danger and uncertainty of the outside world while foreshadowing the peril he would encounter. This deliberate process ensured that each element added meaning and contributed to the narrative. (Stordahl, 2025, para. 6)

It is important to note the assessment requires that inquiry guides art-making. Thus, the written inquiry statement is a valuable tool aiding the student's ability to narrow their art-making exploration and discovery to a targeted focus and clarifies the presented visual evidence. However, at the heart of the sustained investigation portfolio component is an art-making focus on practice, experimentation, and revision of materials, processes, and ideas. The written inquiry statement guides art-making exploration and substantiates the visual images submitted for evaluation.

The sustained investigation process aligns closely with PBLWorks's Gold Standard PBL: Essential Project Design Elements, which emphasizes sustained inquiry, student voice and choice, opportunities for critique and revision, and reflection (Buck Institute for Education: PBL Works [PBL Works], n.d.). In AP Art and Design, students are given the time and space to work like artists, gradually developing a portfolio that reflects both their skills and their creative process. The rubric for the sustained investigation portfolios emphasizes inquiry and student reflection, promoting a cycle of learning, reflection, and revision. Students are encouraged to describe how their sustained investigation was guided by inquiry and demonstrates practice, experimentation and revision of materials, processes, and ideas.

In contrast to the Sustained Investigation analytic rubric, readers use a holistic rubric to assess the second portfolio component, Selected Works (Appendix B). This component measures student accomplishment in portfolio skills and their ability to synthesize materials, processes, and ideas in finished artworks. Although the Selected Works component does not include formal writing prompts, student writing accompanies each final work, providing information on the students' idea(s), materials, and process(es). In Figure 3, 2023 AP 3-D Art and Design student Audrey Nordfelt created a composite image showcasing scale and detail in her sculptural work. Nordfelt provides information on her idea of perception and developing individual meanings. The idea explanation aids interpretation and understanding of the visual image, and when combined with a materials description "cone 10 clay, high fire glazes layered for custom effect, K9 & Las Vegas Red" and process(es) "sculpted hollow form, added hollow tentacles, factoring in balance, fired in reduction, added base" (Nordfelt, 2023, para 1), the viewer gains insight into how the artwork was developed and executed to fulfill the student's vision.

Figure 3.



Note. From *Currents*, by A. Nordfelt (2023), 2023 AP Art and Design Exhibit (https://apartanddesign.collegeboard.org/2023-student05).
© 2023 A. Nordfelt. Reprinted with permission.

When scoring the Selected Works portfolio component, readers review the digitally submitted student works, the accompanying text clarifying idea(s), materials, and process(es) and use a scale of 1–5 to assign a score (See the Selected Works Scoring Guidelines in Appendix B). The Selected Works are worth 40% of the student's total AP Art and Design score.

Section II: Training and Course supports

AP Art and Design Course Rubrics and Scoring Guidelines

The rubrics and scoring rules (Appendixes A and B) are consistent from year to year and available for teacher and student use on College Board's website, AP Central. AP Central also hosts a web page for each portfolio (2-D Art and Design, 3-D Art and Design, and Drawing) and includes sample student portfolios, providing written and visual evidence for each rubric score point in the sustained investigation and selected works portfolio components. The samples include written commentary from experienced AP Art and Design readers (comprised of high school art educators and higher education faculty) who relate student work to the rubric and describe how each sample achieved a score point. Many high school teachers use the sample student portfolios in conjunction with the course rubrics in low-stakes formative assessments as a way for students to discuss, critique, and practice applying the course rubrics to visual and written evidence. For example, students may use the rubrics to guide conversation during an in-class critique of student artwork and writing. Students might also work in small groups to discuss artmaking progress using specific course rubric content (including definitions) as a focus. In gallery walks (where all student artwork is on display for review), students can use Post-It notes and write feedback aligning with rubric language. The AP Art and Design course rubrics are often printed and added to student sketchbooks for ongoing personal review and reference.

Most importantly, the rubrics direct students toward essential art-making practices inherent to learning and growing through practice, experimentation, and revision of materials, processes, and ideas through an inquiry-based approach. For example, to achieve the highest score in Row B of the Sustained Investigation rubric, students must provide "visual evidence of practice, experimentation, and revision demonstrat[ing] development of the sustained investigation." This statement ensures students provide evidence that they have practiced, experimented, and revised their materials, processes, and ideas in pursuit of an in-depth investigation over time. To achieve the highest score in Row C of the Sustained Investigation, students must provide evidence of the "visual relationships among materials, processes, and ideas and demonstrate synthesis." Students who achieve synthesis have practiced, experimented, and revised throughout their portfolio as they worked towards the coalescence of materials, processes, and ideas. The rubric structure outlines ways students can successfully produce art while providing language that guides discussion and feedback through various formative assessment practices.

Teaching and Learning Supports

The AP Art and Design Course and Exam Description (CED) is a conceptual framework outlining course skills and content applicable to lesson planning through Big Ideas, Learning Objectives, and Essential Knowledge Statements. It is available for download from each AP Art and Design portfolio (2-D, 3-D, or Drawing) hosted on College Board's webpage, and instructors are encouraged to print and share the CED with students. As noted above, the redesign of AP Programs allowed College Board to create new resources for teachers and students. For AP Art and Design, these resources serve to clarify CED expectations. Experienced high school AP Art and Design teachers and college or university faculty host a series of on-demand short videos, called AP Daily Videos, in College Board's learning management system, AP Classroom. The AP Daily Videos clarify ideas in the CED by offering targeted lessons that teach curricular concepts in 7–15 minute segments. AP Art and Design teachers can assign videos to their students through AP Classroom to watch as part of daily work, and students can review as a class, as a small group, or individually. To ensure students understand how the AP Art and Design rubrics are applied when scoring student portfolios, AP Classroom additionally hosts rubric training videos that compare student examples to course rubrics and explain how students achieve rubric points. The same rubric training videos are used to norm readers to the exam requirements and rubric application during the annual AP Art and Design portfolio assessment (Reading). This transparency ensures all students and teachers can access the current visual and written rubric explanations as student work develops and before the final portfolio assessment occurs. Using the CED and companion AP Daily Videos, students are guided on developing their visual art images and works to align with the summative course rubrics and scoring guidelines.

Finally, College Board's website page for AP Arts Webinars also hosts free, ondemand webinars such as *Best Practices on Using the AP Art and Design Rubrics*. These resources are designed to be flexible, allowing teachers and their students to watch AP Classroom and webinar videos together, individually, or in small groups. This adaptability enhances any school's AP Art and Design curriculum, catering to different learning styles and situations.

AP Art and Design Exhibits

College Board's AP Art and Design Exhibit (College Board, 2024) is an annual exhibition showcasing exemplary student artwork. During the yearly AP Art and Design Reading, leaders review student portfolios and choose student artworks representing diverse artistic approaches and ideas, student demographics, and school locations. In total, each year's exhibit includes an average of 50 students. After the initial curation process, students are invited to submit high-resolution images of their selected artworks and create a student statement for publication. In the statements, students respond to prompts that guide them in explaining how they came up with their inquiry idea and how it developed during the school year. Their explanations also clarify the portfolio rubric (e.g., their intentionality in choosing materials and developing processes to support ideas and achieve synthesis). The guided student explanations showcase their work and teach other students (and teachers). Additionally, the student's art teachers and school leaders share best practices for ways in which they support teaching and learning in AP Art and Design. Teachers often write about how they support inquiry-based learning, and school leaders explain how they support and promote the visual art program in their schools. The power of the AP Art and Design Exhibit's design is to intentionally showcase student artwork and serve as a teaching and learning tool through exemplars and detailed student, teacher, and school leader best practice explanations. The exhibit is available on the internet and linked to AP Classroom so that teachers can refer to it as a resource that supports the AP Art and Design rubric and scoring guidelines. The exhibit has over 230,000 visits annually, making this teaching tool a valuable resource for instruction and assessment.

Section III: Theories of Assessment in the Service of Learning

All of these elements of the AP Art and Design portfolio program combine to make it an excellent example of Assessment in the Service of Learning. Edmund Gordon (2020) defines this idea as "an approach to Pedagogy in which assessment, teaching, and learning are organically interrelated such that these three processes are dialectically and reciprocally employed each in the service of the other" (p. 73). In many ways, AP Art and Design serves as a perfect illustration of how assessment can be "organically interrelated" with teaching and learning. While it is ultimately a summative assessment leading to the awarding of a final AP score that can be used by colleges and universities to grant students placement or credit for

work done in high school, the AP Art and Design portfolio is intentionally process-focused in a way that allows it to work in the service of learning. As Gordon (2020) puts it, "Assessments should be designed so that the processes of student thought and creation are visible...Portfolios can make visible the scaffolding, both from the teacher and the students' own processes that resulted in the product" (p. 74). The AP Art and Design portfolio works in just that way; in fact, the portfolio submission requires that students detail the processes of thinking that led to the works they have created.

As we have seen, the design of the portfolio requirements and of the rubrics used to evaluate those portfolios specifically creates opportunities for students to demonstrate the processes they used and to explore the steps of learning that took place over the course of the development of their portfolios. In the Sustained Investigation section of the portfolio, students can submit images that document their art-making process, and the rubrics specifically ask for evidence of practice, experimentation, and revision (See Appendix A). The written evidence that students supply also provides opportunities for them to reflect on and discuss their process, the decisions they made, and any development or revisions that came from their investigation of the inquiry topic. Thus, in Row B of the Sustained Investigation rubric, raters are asked to look at both the visual and written evidence. To achieve the highest score on that Row, the work must demonstrate the following: "Visual evidence of practice, experimentation, and revision demonstrates development of the sustained investigation. AND Written evidence describes ways the sustained investigation developed through practice, experimentation, and revision" (See Appendix A). In the literature on Assessment in the Service of Learning, a focus on process is discussed as a multifaceted aspect of assessment that pushes one beyond the realm of mere measurement and into the service of learning.

One aspect of *process* that the AP Art and Design portfolio highlights is student motivation. In asking students to follow a line of inquiry through practice, experimentation, and revision, the portfolio demands and hopefully encourages students to exhibit a certain amount of motivation as they solve problems and develop artworks of their choosing. An inquiry driven curriculum places students in the driver's seat of their learning, providing autonomy (a basic tenet of motivation). In her discussion (2006) of assessment as a "powerful lever for learning," Lorna Earl notes, "In the medium and long term, assessment [holds] the

possibility of...influencing students' motivation as learners and their perceptions of their capabilities" (p. 4). Learning is not a static state that can be simply identified by an assessment, something a student has or has not acquired; rather, it is a "dynamic process" (Earl, 2006, p. 6) that requires active engagement on the part of the learner

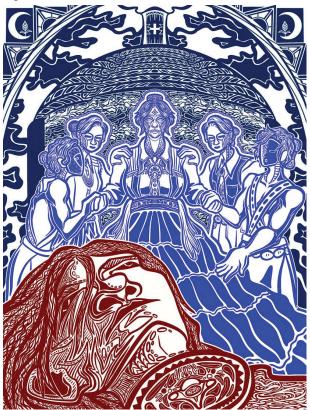
To keep students actively engaged in the learning process throughout the entire portfolio development process, the AP Art and Design program includes a number of features designed to increase student motivation. The heart of the portfolio is the Sustained Investigation section, and a quick look at the Scoring Criteria (See Appendix A) for this section demonstrates factors that are linked to motivation. First, the Sustained Investigation section is meant to be guided by an inquiry that the test-taker chooses based on their own specific interests, and the first row of the scoring rubric assesses whether or not there is an inquiry and to what extent that inquiry has guided the investigation. That is, test-takers are not simply asked to create individual works of art. They are asked to use their artwork as a vehicle to investigate and explore ideas that are of interest to them.

Additionally, students are asked to solve problems that arise as they conduct their investigation, and problem-solving is a key feature of motivation. As Earl puts it, "Not only are humans able to search for problems to solve; they appear to enjoy it" (2006, p. 5). In the case of AP Art and Design, students can encounter any number of interesting problems, from difficulties composing works to challenges using specific media. The course and portfolio are designed to encourage students to engage with those problems and learn from them. We can see this emphasis on problem-solving in the part of the rubric related expressly to whether or not the test-takers have engaged in "practice, experimentation, and revision [that] demonstrates development of the sustained investigation" (College Board, 2023, p. 41). Test takers can show evidence of this practice, experimentation, and revision by including process documentation in their portfolio. That could be a preliminary sketch or model that led to a more finished work, an image of a piece that was unsuccessful but provided a key idea, or documentation of an artistic idea as shown in Figure 3. Because the focus of the portfolio is on inquiry, investigation, and exploration, test-takers are not required or expected to include only polished, 'perfect' works of art. Because perfectionism can have a negative impact on student motivation (Fletcher & Neumeister, 2012), it can increase motivation to allow test-takers to include works that show growth or learning,

such as process pieces and works that were revised. The explicit focus in the portfolio requirements on "practice, experimentation, and revision" (See Appendix A) allows students the freedom to try new things and fail. In fact, a student's failures can increase motivation in a situation like this because "perfection" is not an expectation or a requirement.

Motivation, in fact, is a key factor enabling someone to continue when a task or process is difficult, and creating works of art can present difficult challenges. Such challenges for AP Art and Design students might be related to the use of a particular medium (paint, ceramics, digital photography, etc.), the attempt to find the proper style to use to communicate a given idea, or solving a problem related to composition, which was a struggle encountered in 2023 by Aanje Greymountain (Greymountain, 2023). In one artwork (See Figure 4), Greymountain was attempting to depict the ending of the Navajo story of the Hero Twins, the moment when the Twins bring the head of the evil giant back to their mother and grandparents. However, she struggled to find the right composition for the piece, something that would depict both the Twins and the head of the giant. As she notes, "I had a tough time creating this piece. For the life of me, I could not find out how to fit in the head of the giant despite it being the central element of the storytelling" and took "much trial and error" (Greymountain, 2023, para. 3) to get to the composition she ended up using, which we see in Figure 4. As we will discuss later, this kind of self-reflection or metacognition is further demonstration of the way that AP Art and Design operates as assessment in the service of learning, literally helping shape the artist's practice and process.

Figure 4.



Note. From Hero Twins, by A. Greymountain (2023), 2023 AP Art and Design Exhibit (https://apartanddesign.collegeboard.org/2023-student01). © 2023 A. Greymountain. Reprinted with permission.

Course instructors for AP Art and Design can help students understand the importance of maintaining motivation in the face of interesting challenges. Greymountain's teacher, Greg Stevens, notes how the structure of the AP course and assessment served as effective motivation, saying,

Through practice, experimentation, and revision, Aanje successfully fulfilled her vision. Sketchbooks were filled with different compositions, details, and subject matter. What started as a verbal story was written down and divided into visual pieces. Those pieces were then vetted through critiques, self-analyzation, and cohesion. Nothing was considered sacred, and everything was up for discussion, debate, and revision... The College Board has provided a structure that allows students to make their art more authentic, conceptual, and personally fulfilling. It's not so much teaching the technical aspects but the behavioral traits of an artist (Stevens, 2023, para. 2).

The AP Art and Design portfolio, then, is structured in such a way as to provide motivation for test-takers, helping them learn the "behavioral traits of an artist" (Stevens, 2023, para. 3) and giving them the tools to solve problems in ways that enhance learning. In addition, many of the tools discussed earlier in the article (e.g., AP Classroom videos and the Exhibition) give teachers the resources they need to help students maintain motivation while solving problems.

In the literature related to assessment in the service of learning, researchers note the importance of engagement as a major factor encouraging student learning, and engagement is another aspect of process that the Art and Design portfolio encourages. Dylan Wiliam, speaking of the forces that drive successful learning, notes, "[T]here is now a strong body of theoretical and empirical work that suggests that integrating assessment with instruction may well have unprecedented power to increase student engagement and to improve learning outcomes" (2011, p. 22). For AP Art and Design, the focus on inquiry, experimentation, and exploration in the portfolio requirements and in the evaluation criteria is designed to enhance student engagement in ways that the former AP Studio Art course and portfolio allowed but did not explicitly encourage. Although AP Studio Art originally had a Concentration section that allowed test-takers to focus on an idea of interest. certain aspects of the evaluation criteria rewarded mastery of technical skill over inquiry. For example, in the previous course, one of the bullets in the scoring quidelines describing the highest score point for the Concentration section read, "In general, the work is technically excellent" (College Board, 2019, p.7). And for many years, the Selected Works section of the portfolio was known as the Quality section, a name that emphasized the focus on mastery of technique and the creation of highly polished, finished works of art. AP Art and Design shifted its focus to inquirydriven investigation. As part of the redesign process described at the beginning

of the chapter, College Board held extensive discussions with college professors and those who run foundation art programs at the college level. The predominant feedback was that college foundations courses prioritize inquiry and investigation over the creation of finished artworks. A quick look at the terminology defined in the scoring criteria reveals the redesigned AP Art and Design course does value exactly these inquiry-related concepts—development, discovery, experimentation, exploration, practice, process, and revision (College Board, 2023b). The glossary defines the key concept, inquiry, as "the intentional process of questioning to guide exploration and discovery over time" (p. 43). And this vision of inquiry, the call for students to ask questions and explore topics of interest to them, helps keep them engaged as they develop the works that are included in their portfolios.

Because students in AP Art and Design are exploring topics of interest to them, they are more likely to be engaged with their work, which leads to greater satisfaction. According to Naomi Holmes (2017), "Student engagement is intrinsically linked to two important metrics in learning: student satisfaction and the quality of the student experience" (p. 23). This sense of satisfaction can lead to enhanced effort and ultimately to stronger performance. There are many examples of engagement in successful portfolios submitted for AP Art and Design. For instance, Audrey Nordfelt, who took the AP 3D Art and Design course in 2023, started out feeling like ceramics were, as her teacher put it, "outside her comfort zone" (Frampton, 2023). As she worked on pieces for her portfolio, Nordfelt (See Figure 5) became increasingly engaged by the idea of perception because people kept telling her what they thought her artworks represented. As she says, "So many people would ask what I was making, and then they would tell me what they thought it was. For the most part, people saw it as different things. This made me curious about perception again. I decided to look into it and research human brains and how we process things we see. I learned that there are different steps to perception" (Nordfelt, 2023). Because she was engaged with this particular idea, Nordfelt was able to overcome her discomfort with the medium she was exploring and create work that was both meaningful to her and successful according to the portfolio scoring guidelines. For her work, *Currents*, featured in the 2023 AP Art and Design Exhibit (College Board, 2023a), she noted that different people saw different shapes or creatures (e.g., anemone or octopus) in it.

Figure 5.



Note. From *Currents*, by A. Nordfelt (2023), 2023 AP Art and Design Exhibit (https://apartanddesign.collegeboard.org/2023-student05).
© 2023 A. Nordfelt. Reprinted with permission.

Nordfelt's research on perception, or the notion that "because we all have learned different things and lived different lives, we all have different knowledge and use that knowledge to perceive things we see differently" (Nordfelt, 2023), promoted the kind of engagement required to create a successful portfolio. As her teacher notes, "Sometimes, students must be encouraged to keep going even when they do not know how it will happen. She went on to win the best of show in our district art competition and created an amazing AP Art and Design portfolio" (Frampton, 2023, para 6). In this case, engagement played a large part in helping this student "keep going."

Section IV: Formative Feedback cycles Supporting Metacognition

In the case of AP Art and Design, the final, summative assessment (the portfolio) is designed to encourage student attention to process, causing the portfolio to function in many ways like a formative assessment. Students put together their portfolios over the course of a year or longer, with regular opportunities for teacher feedback to guide student revisions leading to changes in subsequent works that make the final portfolio more successful. Building on Arkalgud Ramaprasad's classic definition of feedback (1983), D. Royce Sadler notes that "information about the gap between actual and reference levels is considered as feedback only when it is used to alter the gap" (1989, p. 121). That is, the feedback that teachers provide on AP Art and Design portfolio work can be used to improve performance. Thus, it meets William's (2011) requirement of being "information generated within a particular system, for a particular purpose" (p.3), rather than information "separated...from its instructional consequences" (William, 2011, p. 3). Within the AP Art and Design classroom, teachers are consistently working with students to revise and refine works, explore new ideas that could further the inquiry, and learn from both mistakes and successes. The scoring guidelines, which give points for successful experimentation and revision, are explicitly constructed to reward exactly this kind of formative feedback.

Furthermore, the emphasis within the portfolio requirements and the scoring criteria on inquiry keep the students actively engaged in the learning process. The example works discussed above show how the program is designed to encourage motivation and engagement by having students pursue a line of inquiry that is interesting to them (a traditional story important to the student's culture or an intellectual idea that the student finds fascinating). As Earl (2006) notes,

"Learning was long thought to be an accumulation of atomized bits of knowledge that are sequenced, hierarchical, and need to be explicitly taught and reinforced. Learning is now viewed as a process of constructing understanding by attempting to connect new information to what is already known so that ideas have some personal coherence" (p. 4). Following a line of inquiry through experimentation and revision in the AP Art and Design portfolio requires students to do exactly that—construct understanding by connecting new information to what is already known.

The formative feedback cycles that the AP Art and Design portfolio allows for, and that the scoring criteria encourage, support students in a specific form of feedback, namely metacognition, which "occurs when students personally monitor what they are learning and use the feedback from this monitoring to make adjustments, adaptations and even major changes in what they understand" (Earl, 2006, p. 7). Take, for instance, the focus in the Sustained Investigation section on revision as one of the key skills test-takers need to demonstrate. Throughout the process of developing a portfolio, a student is asked to look at the work they have already created and make adjustments based on what they have learned, what has worked, and what has not come across as they expected. That is, the student must engage in metacognition in relation to the works that have already been created, thinking about the thinking that went into each piece and making adjustments as they progress. Using this type of metacognition can help learners to "understand and control their own cognitive processes" (Hands & Limniou, 2023, p. 125). Student development of metacognitive strategies has been tied to better learning outcomes, such as moving from surface to deep learning approaches (Hands and Limniou, 2023), and it is theorized to "play a fundamental" role in guiding students' learning across domains" (Taouki, Lallier, & Soto, 2022, p. 921). Supporting these metacognitive activities was an active goal of the Art and Design redesign process, and we see clear evidence that the new portfolio requirements do, indeed, encourage this kind of thinking.

As the AP Art and Design *Course and Exam Description* points out, the process of investigation that is at the core of the work done to develop a portfolio "can confirm and challenge thinking, revealing connections and opportunities" (College Board, 2023, p. 14). Students are encouraged to focus on this metacognitive process both by the portfolio design with its emphasis on inquiry and by the fact that Row B on the Sustained Investigation scoring guide explicitly assesses whether the works demonstrate Practice, Experimentation, and Revision (See Appendix A). That is,

students are directly rewarded for metacognitive practices like making revisions based on examining and thinking about the results of an earlier attempt.

For an excellent example of the way metacognition can influence the development of the artworks going into a specific AP Art and Design portfolio, we can look at the work of Elizabeth Tian (See Figure 6), who submitted a Drawing portfolio in 2023 and had work that appeared in the 2023 Exhibition (College Board, 2023). According to Tian, "The state of mind can be a place of disruptions, brawls, celebrations, or serenity" (2023, para. 2). Because she was aware of and able to reflect on those different, conflicting states of her mind, she was determined to create works that "depict a visual strain that reflects one's emotional strain" (Tian, 2023, para. 2) related to the pressures that society places on each individual due to unrealistic expectations. In the piece Gasping, we see this metacognitive exploration developed visually. Tian claims this piece explores the "accumulation of immense pressure that is overwhelmed by its constantly changing surroundings" (Tian, 2023, para. 9). In the work, Tian includes "cheeky laughing and screaming mouths, frantic eyeballs, and crooked, yellowed teeth" to visually demonstrate the idea that "society tries to draw people into what they see, say, and feel" (Tian, 2023, para. 3). Thus, her thinking about the way society impacts a person, creating tension and distortions, led to Tian's experimentation with both content (exaggerated and distorted features) and form. Grasping is a self-portrait, in which the artist is surrounded in a swirl of grotesque figures, representing directly the kind of social pressure Tian is investigating, depicting her "struggle to cry out, gasping for relief" (Tian, 2023, para. 3). And yet, the work contains balance and symmetry. There is order and beauty that indicates the relief and peace that lie beyond the tension Tian is exploring. As she notes, the tension we all experience "will soon be released because we evolve as we experience it" (Tian, 2023, para. 2). It is this level of metacognition and recognition that the AP Art and Design program both allows and encourages students to reach

Figure 6.



Note. From Flooding, by E. Tian (2023), 2023 AP Art and Design Exhibit (https://apartanddesign.collegeboard.org/2023-student14).
© 2023 E. Tian. Reprinted with permission.

Section V: Engaging Community through AP Art and Design: Learners, Teachers, Administrators, and Families

Presentation

When students embark on their journey to produce a portfolio of work for AP Art and Design, the production and exhibition of their work is often a community affair. From informal class critiques to formal end-of-year art shows, the visual art students present their work throughout the art-making process. College Board's CED (2023b) speaks to presentation and audience engagement like Nordfelt (2023) sought to engage others through perception. Both focus on interpretation as part of presentation. Essential Knowledge Statement 3.F.1 informs teachers and students that

Presenting works of art and design to viewers for interpretation involves making decisions about what to show, when to show it, how to show it, and to whom it is shown. Different ways of presenting work can lead to different interpretations—even for the artist or designer who made the work. The artist or designer has the power to affect how materials, processes, and ideas within a work are perceived, based on decisions they make about how they present or display the work (p. 27).

Students are thus directed to intentionally engage their audience through presentation choices to affect interpretation. Artworks, by nature, are meant to be viewed and interpreted, leading to conversation and dialogue about artistic intention and purpose. The CED further directs student artists that presentation "can include communication[s] between the artist or designer and the viewer" to "inform thinking and making" (College Board, 2023b, p. 27). Communication may occur through discussion, writing, and even visual responses. The CED advises students to consider how "documentation can include viewer interpretations of the work presented. Documentation of presentation becomes a resource for the artist/designer and it can be shared with viewers" (College Board, 2023b, p. 27). A student artist has the capacity to engage others by developing a dialogue through presentation processes. In part, this kind of dialogue begins in the classroom through critiques focused on presenting, interpreting, and providing feedback on artwork.

Formative assessment

Visual art critiques are an integral form of formative assessment in an art and design curriculum. By their nature, art class critiques develop a sense of peer community through shared purpose and meaningful engagement around art-making. Students struggle together to communicate ideas, improve art-making practices, discuss processes, and create a finished project. Art critiques can be short teacher and student feedback sessions lasting minutes to several days of classroom conversation focused on an entire class's artwork development. An art critique typically involves a presentation of the final artwork or work in progress followed by a discussion of the ideas, material choices, and processes used. Some critiques are teacher-directed, while others are collaborative activities with whole class engagement. Dan Kuffel, a teacher whose student College Board curated into the 2023 AP Art and Design exhibit, wrote in his teacher statement that he supports student learning by

encourage[ing] students to work in small groups to promote the cross-pollination of ideas. Having a sounding board, opposing perspective, friendly ear, or complete collaborator as you create your best work. These also act as informal critiques while the works are developing. Work is shared and refined, and usually, your friends will tell you the truth (Kuffel, 2023, para. 7).

In this capacity, learners are engaged and motivated to participate, to help and encourage each other, to develop friendships, and to understand ways to improve. Honest communication and relationship-building through art production are foundational to building trust. Making and presenting art is a vulnerable process, and trust is integral to supporting authentic communication and creativity. Maggie Jones, another teacher whose student, Aundrea McCarthy, was curated into the 2023 AP Art and Design Exhibit, wrote in her teacher statement that "critique sessions serve as collaborative forums, where students offer each other constructive feedback, fostering a sense of community within our creative space" (College Board, 2023, para. 3). Through critique, learners present and reflect, document their learnings from peer or teacher reviews, and discuss learnings in ways unique to the visual arts. Critiques provide regular feedback cycles that enhance student ideas, skills, and artistic growth. Presentation and critique practices build community engagement in the classroom that can parallel how professional artists engage with others.

School and Community Engagement

College Board's CED guides teachers and school administrators to consider that "students need time and resources to engage with art and design in the classroom, school, and in the local community as well as in museums and galleries (in person and virtually)" (College Board, 2023b, p. 5). While visual art critiques are one way to engage and build community, extending the visual arts curriculum into the community is another. It is crucial for students to engage with art and design in various settings, as it broadens their perspective and enhances their learning experience. Virtual or in-person field trips or gallery visits allow students to engage with how adult artists think, create, and present their art. When students perceive how adult artists grapple with art-making to communicate ideas with their processes, they may gain insight into how they, as young artists, may fit into a broader art-making community. This kind of external connection or meaning-making builds purpose and reinforces internal motivation. When AP Art and Design students discover how or why their voice matters in a larger context, their inquiry goals become even more meaningful.

Visual art teachers are generally creative in forming community within their classroom, school, and local community. In a statement about her featured student in the 2023 AP Art and Design Exhibit, educator Emily Lemp writes, "...we often have showcases and gallery walks throughout the school year and partnerships with outside organizations that host some of these events, such as the law firm Cleary Gottlieb" (College Board, 2023, para. 2). By working with an external sponsor, Lemp can build relationships between a law firm and student artists to support and engage the school community in ways appropriate to the school context. Another featured educator in the 2023 exhibit, Suzanne Zimmerman, writes in her teacher statement that the AP Art and Design program advances students because she builds relationships with local designers and creative mentors. She adds,

We show work annually at our local art center in a professional gallery, a collaboration that has led to internships and employment through networking in the community. Critiques, competitions, school art shows, and creating work to sell for charity cultivate a comprehensive picture of how to be an engaged artist and activist in practice. We try to help our young artists thrive professionally and personally by learning to apply creative problem-solving, community, confidence, and perseverance in the art studio and their other life adventures (Zimmerman, 2023, para. 3).

Building community partnerships between students, the school community at large, and the surrounding community, including businesses and art studios, creates rich programming to engage and support students.

Section VI: Conclusion

AP Art and Design, then, offers an excellent model demonstrating the different process-related aspects of Assessment in the Service of Learning. Because it allows opportunities for formative assessment throughout the development of the portfolio, the program engages students (and their broader communities both inside and outside of the classroom), enhances motivation, and fosters the use of metacognitive strategies. The Course and Exam Description (College Board, 2023a) explicitly drives students toward these different aspects of learning, as it puts the focus of the course and the exam on investigation, experimentation, and revision. Those ideas are essential to the development of the work, but also to the thinking that goes into all aspects of the course, from the decision to explore a particular Sustained Investigation topic to the discussion of works with classmates and the broader community through to the selection of works to present in the portfolio. Each step in the process allows the students to examine the decisions they have made, look at the impacts of those decisions, and adjust. This metacognitive work fosters deeper learning (Hands & Limniou, 2023), which is evident in the outcomes seen for students who have taken AP Art and Design. More studies should be done to evaluate the impact of AP Art and Design on student learning, but the preliminary results (Escoffery et al., 2025) point to the idea that theories of assessment in the service of learning do result in strong learning gains.

References

- Buck Institute for Education (PBLWorks). (n.d.). *Gold standard PBL: essential project design elements*. PBL Works.
 - https://www.pblworks.org/what-is-pbl/gold-standard-project-design
- College Board. (2019). AP Studio Art scoring guidelines (Effective 3/15/2019) [AP Reading Training Material].
- College Board. (2023a). AP Art and Design course and exam description (Effective Fall 2023). https://apcentral.collegeboard.org/media/pdf/ap-art-and-design-course-and-exam-description.pdf
- College Board. (2023b). 2023 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2024-ap-art-and-design-exhibit
- College Board. (2024). 2024 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2024-ap-art-and-design-exhibit
- Council, N. R., Division of Behavioral and Social Sciences and Education, Education, C. F., & Committee on Programs for Advanced Study of Mathematics and Science in American High Schools. (2002). Learning and understanding: Improving advanced study of mathematics and science in U.S. high schools (New ed.). National Academies Press.
- Drew, C. (2011, January 9). Rethinking Advanced Placement. *New York Times*. https://www.nytimes.com/2011/01/09/education/edlife/09ap-t.html
- Earl, L. (2006). Assessment—A powerful lever for learning. *Brock Educational Journal*, 16(1), 1–15.
- Escoffery, D. S., Fletcher, K. E., & Stone-Danahy, R. A. (2025). "A search for my voice": Socioculturally responsive assessment in AP Art and Design. In R. E. Bennett, L. Darling-Hammond, & A. Badrinarayan (Eds.), Socioculturally responsive assessment: Implications for theory, measurement, and systems-level policy (pp. 262–282). Routledge. https://doi.org/10.4324/9781003435105

- Fletcher, K., & Neumeister, K. (2012). Research on perfectionism and achievement motivation: Implications for gifted students. *Psychology in the Schools, 49*(7). 668–677.
- Frampton, R. (2023, December 1). *Teacher statement*. College Board. 2023 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2023-student05
- Gordon, E. (2020). Toward assessment in the service of learning. *Educational Measurement: Issue and Practice*, 39(3), 1–142.
- Greymountain, A. (2023, December 1). *Hero Twins* [digital art, Procreate]. College Board. 2023 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2023-student01
- Hands, C., & Limniou, M. (2023). A longitudinal examination of student approaches to learning and metacognition. *Journal of Higher Education Theory and Practice*, 23(19). 125–150.
- Holmes, N. (2017). Engaging with assessment: Increasing student engagement through continuous assessment. *Active Learning in Higher Education*. 19(1). 23–34.
- Jagesic, S., Ewing, M., Feng, J., & Wyatt, J. (2020). AP capstone™ participation, high school learning, and college outcomes: Early evidence (Research Report No. RR 2020-09; ED603711). Educational Testing Service. https://eric.ed.gov/?id=ED603711
- Jones, M. (2023). *Teacher Statement*. College Board. 2023 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2023-student06
- Kuffel, D. (2023). *Teacher Statement*. College Board. 2023 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2023-student03
- Lemp, E. (2023). *Teacher Statement*. College Board. 2023 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2023-student10
- Nordfelt, A. (2023, December 1). *Currents* [Cone 10 clay, high fire glazes layered for custom effect, K9 & Las Vegas Red]. College Board. 2023 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2023-student05

- Qualls, A. L. (1998). Culturally responsive assessment: Development strategies and validity issues. *The Journal of Negro Education*, 67(3), 296–301. https://doi.org/10.2307/2668197
- Ramaprasad, A. (1983). On the definition of feedback. Behavioral Science, 28. 4-13.
- Sadler, D. R. (1989). Formative assessment and the design of instructional systems. Instructional Science. 18, 119–144.
- Stevens, G. (2023, December 1). *Teacher Statement*. College Board. 2023 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2023-student01
- Stordahl, D. (2025, February 1). Caesar departs from Rome. 2024 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2024-student07
- Taouki, I., Lallier, M., & Soto, D. (2022). The role of metacognition in monitoring performance and regulating learning in early readers. *Metacognition and Learning*. 17. 921–948.
- Tian, E. (2023, December 1). *Flooding* [Watercolor and Pen on cut-up watercolor paper, collaged with glue.]. College Board. 2023 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2023-student14
- Wiliam, D. (2011). Formative assessment: Definitions and relationships. Institute of Education, University of London. 1–26.
- Wyatt, J., Feng, J., & Ewing, M. (2020, December). AP® computer science principles and the STEM and computer science pipelines [PDF]. AP Central. https://apcentral.collegeboard.org/media/pdf/ap-csp-and-stem-cs-pipelines.pdf
- Zimmerman, S. *Teacher Statement*. College Board. 2023 AP Art and Design Exhibit. https://apartanddesign.collegeboard.org/2023-student11

Appendix A:

AP 2-D/3-D/Drawing Art and Design: 2024 Scoring Guidelines

Sustained Investigation Rubric

General Scoring Note

When applying the rubric, the score for each row should be considered independently from the other rows. You should award the score for that row based solely upon the criteria indicated, according to the **preponderance of evidence**. Student work may receive different scores for each row

Each row includes decision rules and scoring notes used during the AP Art and Design Reading. Begin with score point 1 when applying the decision rules.

Row	Scoring Criteria			
A	Inquiry Writing Prompt 1: Identify the inquiry that guided your sustained investigation.			
	1	2	3	
	Written evidence does not identify an inquiry.	Written evidence identifies an inquiry AND Visual evidence demonstrates the inquiry.	Written evidence identifies an inquiry. AND Visual evidence demonstrates the inquiry. AND The inquiry guides the development of the sustained investigation.	
	Decision Rules and Scoring Notes Read the student response to writing prompt 1 .			
	Does the written evidence identify an inquiry by describing discovery and exploration? (A question or a statement that merely identifies a theme or a topic is not an inquiry.) If no, award 1 point. If yes, move to criteria for score point 2.	Does the <i>visual</i> evidence demonstrate the inquiry? If no, award 1 point. If yes, move to criteria for score point 3.	Does the inquiry guide the development of the sustained investigation? If no, award 2 points. If yes, award 3 points.	

Practice, Experimentation, and Revision Writing Prompt 2: Describe ways your sustained investigation developed through practice, experimentation, and revision.			
1	2	3	
Visual evidence of practice, experimentation, and revision does not relate to a sustained investigation.	Visual and written evidence of practice, experimentation, and revision relates to a sustained investigation.	Visual evidence of practice, experimentation, and revision demonstrates development of the sustained investigation. AND Written evidence describes ways the sustained investigation developed through practice, experimentation, and revision.	
Decision Rules and Scoring Notes Read the student response to writing prompt 2 .			
Is there <i>visual</i> evidence of practice, experimentation, and revision? AND Does the <i>visual</i> evidence of practice, experimentation, and revision relate to a sustained investigation? If no (for either or both), award 1 point. If yes (for both), move to criteria for score point 2.	Does the written evidence of practice, experimentation, and revision relate to a sustained investigation? If no, award 1 point. If yes, move to criteria for score point 3.	Does the visual evidence of practice, experimentation, and revision demonstrate development of the sustained investigation? AND Does the written evidence describe ways the sustained investigation developed through practice, experimentation, and revision? If no (for either or both), award 2 points. If yes (for both), award 3 points.	

С	Materials, Processes, and Ideas				
	1	2	3		
	Little to no evidence of visual relationships among materials, processes, and ideas.	Visual relationships among materials, processes, and ideas are evident.	Visual relationships among materials, processes, and ideas are evident and demonstrate synthesis.		
	Decision Rules and Scoring Notes In this row, written evidence is not scored but reading student responses may inform the evidence of visual relationships.				
	Is there evidence of visual relationships among materials, processes, and ideas? If no, award 1 point If yes, move to criteria for score point 2.	Do the visual relationships among materials, processes, and ideas demonstrate synthesis? If no, award 2 points. If yes, award 3 points.			

D	2-D/3-D/ Drawing Skills				
	1	2	3		
	Visual evidence of rudimentary and moderate	Visual evidence of moderate and good	Visual evidence of good and advanced		
	2-D/3-D/Drawing skills.	2-D/3-D/Drawing skills.	2-D/3-D/Drawing skills.		
	Decision Rules and Scoring Notes				
	Does the <i>visual</i> evidence include some works with good (proficient) skills? If no, award 1 point.	Does the <i>visual</i> evidence include some works with advanced (highly developed) skills?	Does the <i>visual</i> evidence across all works include a range of good to advanced skills?		
	If yes, move to criteria for score point 2.	If no, award 2 points. If yes, move to criteria for score point 3.	If no, award 2 points. If yes, award 3 points.		

AP Art and Design Sustained Investigation Rubric Terminology (in alphabetical order)

- **2-D Art and Design Skills:** The application of two-dimensional elements and principles—point, line, shape, plane, layer, form, space, texture, color, value, opacity, transparency, time; unity, variety, rhythm, movement, proportion, scale, balance, emphasis, contrast, repetition, figure/ground relationship, connection, juxtaposition, hierarchy
- **3-D Art and Design Skills:** The application of three-dimensional elements and principles—point, line, shape, plane, layer, form, volume, mass, occupied/unoccupied space, texture, color, value, opacity, transparency, time; unity, variety, rhythm, movement, proportion, scale, balance, emphasis, contrast, repetition, connection, juxtaposition, hierarchy

Advanced: Highly developed

Demonstrate: To clearly show

Describe: Using words to communicate relevant information

Development: The furthering or advancing of an inquiry in a sustained investigation (through in-depth exploration of materials, processes, and ideas)

Discovery: To learn something through the process of making

Drawing Skills: The application of mark-making, line, surface, space, light and shade, composition

Experimentation: testing materials, processes, and/or ideas

Exploration: A journey of experimentation and discovery directed by inquiry

Evidence: To make obvious, seen, or understood

Good: proficient

Guides: The inquiry leads the process of making works of art and design

Ideas: Concepts used to make works of art and design (evident visually or in writing)

Identify: Indicate or provide information

Inquiry: The intentional process of questioning to guide exploration and discovery over time

Intent: The purpose or reason for exploring an idea

Materials: Physical substances used to make works of art and design

Moderate: Adequate

Practice: The repeated use of materials, processes, and/or ideas

Processes: Physical <u>and</u> conceptual activities including applications involved with making works of art and design

Questioning: Purposeful investigation and discovery in relationship to an idea

Reimagine: Reinterpret with imagination; rethink

Relate: Having a relationship and/or connection between

Revision: To modify, clarify, or reimagine works and ideas

Rudimentary: Emerging or undeveloped

Sustained Investigation: An inquiry-based and in-depth study of materials, processes, and ideas over time

Synthesis: Coalescence/integration of materials, processes, and ideas

Visual Evidence: The visual components that make up the student's works of art and design

Visual Relationships: Connections between the visual components included in a student's works of art and design

Ways: A series of actions or events leading in a direction or toward an objective

Written Evidence: The written components that accompany the student's works of art and design

Appendix B:

AP 2-D/3-D/Drawing Art and Design: 2024 Scoring Guidelines

Selected Works Rubric

General Scoring Note

When applying the rubric, you should award the score according to the **preponderance of evidence**; the response may not meet all three criteria indicated. However, if the written evidence is completely unrelated to the works, the **maximum** possible score is 2.

Scoring Criteria A. Written Evidence B. 2-D/3-D/Drawing Skills C. Materials, Processes, and Ideas The Selected Works demonstrate 1 2 A. Written evidence may identify may identify identifies identifies identifies materials, materials, materials. materials. materials. processes, and processes, and processes, and processes, and processes, and ideas. ideas. ideas. ideas. ideas. B. Visual evidence B. Visual evidence B. Visual evidence B. Little to no B. Visual evidence visual evidence of rudimentary of moderate of good 2-D/3-D/ of advanced of 2-D/3-D/ 2-D/3-D/ 2-D/3-D/Drawing Drawing skills. 2-D/3-D/ Drawing skills. Drawing skills. skills. Drawing skills. C. Visual C. Little to no C. Little to no C. Visual relationships C. Visual evidence evidence relationships relationships among of visual of visual among materials, among relationships relationships materials, processes. materials, among among processes, and ideas are processes, materials, materials, and ideas are evident. and ideas are processes, and processes, and evident but may evident and ideas. ideas be unclear or demonstrate inconsistently synthesis. demonstrated.

Decision Rules and Scoring Notes

A. Review written evidence:

If the written evidence does not identify materials, processes, and ideas, the portfolio is only eligible for score points 1 and 2.

If the written evidence identifies materials, processes, and ideas, the portfolio is eligible for all five score points.

B. Review the application of 2-D/3-D/Drawing art and design skills to determine accomplishment level:

accomplishment level:								
1	2	3	4	5				
Not present or Emerging and unclear undeveloped		Adequate	Proficient	Highly Developed				
C. Read the written evidence and then evaluate the visual relationships among materials, processes, and ideas:								
1	2	3	4	5				
Little to none	Little to none	Evident, but unclear or inconsistently demonstrated	Evident	Evident and demonstrates synthesis				

AP Art and Design Selected Works Rubric Terminology (in alphabetical order)

- **2-D Art and Design Skills:** the application of two-dimensional elements and principles—point, line, shape, plane, layer, form, space, texture, color, value, opacity, transparency, time; unity, variety, rhythm, movement, proportion, scale, balance, emphasis, contrast, repetition, figure/ground relationship, connection, juxtaposition, hierarchy
- **3-D Art and Design Skills:** the application of three-dimensional elements and principles—point, line, shape, plane, layer, form, volume, mass, occupied/unoccupied space, texture, color, value, opacity, transparency, time; unity, variety, rhythm, movement, proportion, scale, balance, emphasis, contrast, repetition, connection, juxtaposition, hierarchy

Advanced: highly developed

Demonstrate: to clearly show

Drawing Skills: the application of mark-making, line, surface, space, light and shade, composition

Evidence: to make obvious, seen, or understood

Good: proficient

Ideas: concepts used to make works of art and design (evident visually or in writing)

Identify: indicate or provide information

Inconsistent: not demonstrated in the same way or to the same degree across works of art and design

Materials: physical substances used to make works of art and design

Moderate: adequate

Processes: physical <u>and</u> conceptual activities involved with making works of art and design

Rudimentary: emerging or undeveloped

Selected Works: works of art that demonstrate synthesis of materials, processes, and ideas using 2-D/3-D/Drawing skills

Synthesis: coalescence/integration of materials, processes, and ideas

Unclear: not easily observable, discernable, or legible

Visual Evidence: the visual components that make up the student's works of art and design

Visual Relationships: connections between the visual components included in a student's works of art and design

Written Evidence: the written components that accompany the student's works of art and design

Research & Development Contributions to Assessment, Learning, Games, and Technology

Eva L. Baker and Gregory K. W. K. Chung

Abstract

This chapter presents a survey of illustrative examples of CRESST's R&D contributions to assessment, learning, games, and technology. The mission of CRESST was to understand the meaning of educational quality, including approaches involving evaluation and assessment. Examples from four major areas of R&D are presented: studies of writing assessment, the assessment of rifle marksmanship, evaluation of artificial intelligence systems, and game-based learning and assessment. A foundational element of the R&D was the exploration of assessment design, development, and validation in the context of learning, both as supporting the attainment of learning goals and as an outcome measure. Every example includes the importance of designing assessments to map to the purpose of evaluation and to provide as much transparency as possible. The examples illustrate the Handbook principles of transparency, purpose and focus, and validity.

Author Note

Eva L. Baker, ORCID: https://orcid.org/0000-0001-7347-2170

Gregory K. W. K. Chung, ORCID: https://orcid.org/0000-0003-4380-5661

We have no conflicts of interest to disclose. Correspondence concerning this article should be addressed to Eva Baker, 300 Charles E. Young Drive North, SE&IS Building, Room 300, Box 951522, Los Angeles, CA 90095–1522.

Email: eva@ucla.edu

There was a time within memory when educational research and development was embraced as both important to develop new knowledge in the education and training world and for use as a scientific resource for the development of new applications intended to solve persistent problems. This chapter will highlight a few of the many contributions of the community, but it is tightly limited to a selection of work conducted at the National Center for Research on Evaluation, Standards, and Student Testing (CRESST). We describe four examples of programmatic research that took place over multiple years supported by the U.S. Departments of Education and Defense augmented by private support. The examples demonstrate CRESST's long-term commitment to designing assessments that uphold the core Assessment in the Service of Learning (AISL) principles of *transparency*, *purpose* and *focus*, and *validity*. The examples will also illustrate that developing assessment in the service of learning is not a new or abstract ideal for CRESST, but a throughline that has guided its work for decades.

CRESST was originally developed in the mid-1960s as the Office of Education (prior to the inception of the United States Department of Education) responded to the reauthorization of Title I of the Elementary and Secondary Education Act. The response was a competition for a network of topically focused Research and Development Centers and a Network of Regional Education Laboratories focused on translation and development of usable educational options. UCLA received the 5-year award to focus on evaluation and supporting measurement and methodology in 1966 as the Center for the Study of Evaluation (CSE). Because these awards were developed to optimize the creativity of the scholars in the field, there was considerable latitude given to the design and management of research and development. When the Center grants were recompeted in 1984, CRESST was formally funded as a composite Center, where the focus was on assessment for use in schools, and partners of UCLA included universities, such as the Universities of Colorado, Illinois, and Stanford. CRESST also augmented its award with resources from state, local, federal, and private organizations.

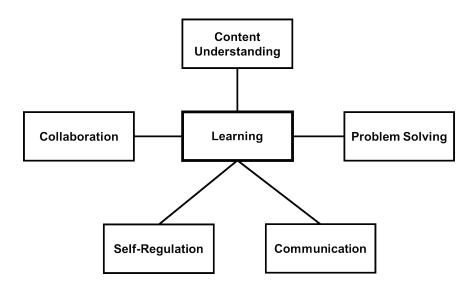
Context of CRESST Research Design

During the period in which the research programs in this chapter occurred, three important conditions prevailed. First, the management of CRESST had extensive flexibility to select, compete, and conduct its research along with its scholars and students. It also was able to modify and adapt its objectives and procedures with little interference from the funding agencies. The ability to follow the directions of findings and to revise ongoing research plans is almost unheard of within recent funding from the federal government and as it may be in the future. Second, CRESST was a mission-focused organization. The mission of CRESST was to understand the meaning of educational quality including approaches involving evaluation and assessment. Technical studies to improve the scientific and statistical basis of the mission were an important concern, as was the exploration of alternatives to prevailing assessment approaches for policy uses. The third important element was to explore assessment in the context of learning, both as it supported the attainment of goals and as an outcome measure. In these efforts we collaborated with state and local agencies and specific organizations in the Department of Defense, including training for Army, Navy, and Marine Corps personnel.

A general model for the development of assessments was proposed and evolved over the years (Baker, 2007). Its central focus was learning supported by the various cognitive and domain requirements to promote the growth of learners. The original model, from Baker (1997), is displayed in Figure 1.

Figure 1.

Areas of Learning Identified for Model-Based Assessment (Baker, 1997)



The notion of the model also derived from research in computer science. This model was meant to be of general purpose and to be implemented in a variety of subject-matter domains. The idea of a general implementation, rather than an assessment approach that started with the subject matter, was a point of departure from traditional practice. Over the years, CRESST continued to develop and elaborate the model, for instance, using ontologies (Baker, 2007, 2012) to set boundaries for both subject matters to be included as well as the forms in which problem-solving would occur. Three criteria were developed to evaluate the quality of assessment: validity, utility, and credibility, all operating within an expectation of fairness and transparency.

The Examples

We include four examples of assessment and evaluation projects that had long-term programmatic reach. In each, we underscore the importance of learning and an understanding of both expert and learner perspectives. The principles animating this Handbook are also in play and include *transparency*, *purpose*

and focus, and validity. The first example we present is an effort that began with history assessment and developed into a writing assessment approach that was of general use. The second is the development of an approach to measure rifle marksmanship knowledge and skills. Both areas used expert performance as a criterion of quality as well as created models of transparent infrastructure that could be used in other assessment requirements. They were intended to focus simultaneously on learning-based assessments and outcome performance in a transparent manner. The third project focused on the development and evaluation of early versions of artificial intelligence including expert systems, natural language, and vision implementations using human benchmarking to measure the progress of AI systems. Our work also evaluated intelligent tutoring, games, and simulations. The fourth area extended R&D in learning game development and evaluation.

Simultaneously, CRESST was engaged in work in policy domains connected to local, state, federal, and international organizations focused on improving assessments, and their clarity, connection to learning and instruction, and attainment of learning goals.

Studies on Writing Assessment

This section will describe the R&D undertaken by CRESST in writing assessment. Its purpose was to apply our assessment model and develop a usable framework for the design and implementation of writing tasks to be used both in instruction and assessment of outcomes, and ultimately was generalized to other forms of constructed responses. The work involved emphases on the development of tasks to support the knowledge needed by students for writing and the ways in which scoring rubrics could be transparently designed to describe and to foster learning to write through feedback. CRESST began its interest in writing assessment in the late 1970s and focused on designs to assist state assessment agencies and to support an international study of written composition (Gorman et al., 1988). Around that time there were efforts by the Bay Area Writing Project (bawp.berkeley.edu), later the National Writing Project (www.nwp.org), to modify the way in which writing instruction took place, that is, to emphasize the process of planning, drafting, and revision. This approach also ultimately became an important part of classroom practice and assessment.

Writing Task Design: Prompt Development Supporting Prior Knowledge

We believed the writing process was only part of the solution, for our analyses and experience suggested that the design of writing tasks was not at all transparent or focused on student background. For essays to be used to evaluate content understanding, an approach was needed to capture students' prior experience. From our earlier studies, we had become convinced that students could not write well about topics on which they had little prior knowledge and that writing was not principally about appropriate style, organization, and mechanics, like punctuation and grammar, but about communicating, an approach supported by the work of Scardamalia et al. (1984). At early meetings of the IEA study on Written Composition (Gorman et al., 1988), we learned that colleagues provided content resources to writers to equalize prior knowledge and to help them flesh out their writing. CRESST staff eventually helped design tasks and scoring systems for the IEA research (Baker, 1982; Baker & Quellmalz, 1986). When CRESST was tasked by the federal government to develop secondary school history assessments, we chose to use writing as the scalable response mode to measure domain understanding. Starting with 10th grade U.S. history, we began an analysis of that content included in popular textbooks to understand student knowledge to be assessed. Unfortunately, we discovered that the treatments of important topics, such as the causes of the Civil War, were presented superficially in a paragraph of text or two and could at best provide the learner with only a thin layer of knowledge. Modeling the IEA R&D, we provided the learners with relatively short primary sources from the period of interest, using contrasting positions of politicians, for instance, the debate speeches by Abraham Lincoln and Stephen Douglas. We followed this model using opposing letters or speeches for the Revolutionary period, the Civil War, immigration in the early 20th century, and World War II among other key events in U.S. history.

Students were to read the given primary sources and then to write an essay in letter form to an absent classmate explaining the meaning of the contrasting positions. Note that over the years, we created similar assessment tasks using primary sources in history, geography, social studies, multidisciplinary topics, and science, where students read about situations and experiments rather than contrasting positions (Baker et al., 1990). In one scaled effort, we applied this approach to statewide trials in the state of Hawaii, using content in Hawaiian history and social studies topics for younger students in upper elementary school (Baker et al., 1991, 1996).

Improving on Scoring Approaches

Simultaneously, the team embarked on approaches to improve scoring by making it more transparent and valid. As noted, our interests were both outcome measures and essays assigned during courses. In both cases, the task was to improve the quality and validity of the scoring, to focus on elements that could be used for student feedback, and to reduce the time burden on teachers that scoring assigned essays imposed. The last point was critical because we had learned that teachers often severely limited the number of writing assignments given to students simply because they had no time to evaluate them. We intended to find evaluation approaches that got to the core of performance without requiring the traditional annotation and lengthy comments by teachers. Moreover, there were also approaches at the time that argued that every writing assignment required its own scoring rubric (See for example, Graves, 1978). While the idea of extracting specific information for each assignment made some sense, the reality was that teachers having to learn to use a different scoring rubric for each assignment was an incredibly unlikely outcome. Idiosyncratic scoring regimes also inhibited the ability to monitor student growth in performance over time, where a common criterion is desirable

Do What I Do, Not What I Say

At CRESST, we decided to explore how the design of scoring rubrics could move beyond teachers' agreed-upon preferences. Our question was simple: Could we make inferences from the actual writing of experts to determine criteria for scoring student work? To that end, we asked teachers and other history experts in graduate school to write answers to prompts about epochs in U.S. history using the provided contrasting speeches. Careful analysis of the experts' writing found they organized their answers using principles or themes, they brought to bear prior knowledge external to that in the provided prompts, they used concrete examples to support their position often from the provided resources, and they avoided major mistakes or misconceptions. To use models of expertise proposed by renowned cognitive researchers (e.g., Chi et al., 1988; Ericsson & Charness, 1994; Gentner & Genter, 1983) we conducted expert-novice studies to confirm common elements in expert writing. An additional set of research involved developing and validating rater training (Quellmalz, 1982) where we focused on accuracy and speed, as we wished to support opportunities for more writing for students.

Impact and Future

The consequences of our work resulted in the development of writing approaches used for a number of state assessments, NAEP (Baker, 1981; Baker et al., 1986), and for multiyear work across literacy and mathematics domains at the elementary school level in the Los Angeles Unified School District (Niemi & Baker, 1998). We also applied these analyses to the evaluation of A level writing in Great Britain (Baker et al., 2002). Current work in AI scoring should include models generated by expert raters rather than simply interpreting identified rubrics. Our current work has focused on the identification of assessment tasks using AI-defined ontologies and domain task generation.

One of the most enduring outcomes of the studies on writing was the generality and utility of the CRESST assessment model and its emphasis on starting with learners and learning outcomes to drive the design of assessments and measures at CRESST (Baker, 1997, 2007; Baker & Gordon, 2014; Baker et al., 2022; O'Neil et al., 1990).

Assessment of Rifle Marksmanship

One of the most remarkable achievements in United States Marine Corps (USMC) marksmanship training is in developing a shooter's skill to routinely hit a 19-inch circular area at 500 yards in the prone position. The challenge posed to CRESST was to develop a way to assess marksmanship in a distance learning context with the goal of helping the USMC improve their non-infantry Marines' marksmanship skills.

In order to develop assessments of what was commonly believed at the time essentially a motor task, without being able to directly observe the shooter carrying out the task, required CRESST to start a program of research from first principles. Many of the methodologies developed for writing assessment were adapted for marksmanship. New frameworks and technologies needed to be developed as well, as marksmanship was never studied from an assessment perspective. In the remainder of this example, we describe the R&D program and illustrate how the domain of marksmanship was defined, how the measures were developed and validated, and how novel measurement approaches were used to explore individualizing instruction.

Determinants of Marksmanship Reexamined

At the start of the research, the marksmanship literature was focused almost exclusively on the proper execution of the motor aspects of the factors needed to establish a stable platform for the rifle and the components that underlie aiming. There was almost no conceptualization of marksmanship as a complex skill and little research to draw on to form a coherent assessment framework. To develop assessments of marksmanship that could operate under distance learning conditions, we needed to understand the underlying factors external and internal to the shooter that affected marksmanship performance.

Based on the literature and interviews with subject-matter experts (SMEs), we decomposed marksmanship performance as a function of factors within the purview of the shooter (perceptual-motor, cognitive, affective) and external to the shooter (weather, equipment). This conceptualization mirrored the CRESST assessment model (Baker, 1997, 2007) (See Figure 1). While the individual components of the model differed, how the components were identified and the role of the components as the focus for the assessments remained the same.

A key contribution was incorporating cognitive and affective components into the research. By conceptualizing marksmanship as a complex skill, we could rely on a skill acquisition model to understand how knowledge and performance interacted over time (Ackerman, 1987, 1992; Fitts & Posner, 1967). Skill development is believed to move from a learning phase to a practice phase and then to an automaticity phase. When applied to marksmanship, trainees in the learning phase are attempting to learn the concepts and rules of marksmanship. Trainees in the practice phase know what to do and practice implementing the various rules and procedures. Trainees in the automaticity phase can smoothly execute the skill with little overt consideration of the rules and procedures.

The skill model predicted the poorest performance during the learning phase when trainees are least likely to have acquired and internalized the knowledge required to shoot well (i.e., Marines who do not routinely handle weapons), suggesting measures of knowledge might be the most sensitive. For trainees in the practice and automaticity phases, perceptual-motor measures could be expected to be stronger predictors of performance. Given our population was non-infantry entry- and sustainment-level Marines, we focused on developing assessments for trainees in the learning phase and with the constraint that the assessments would need to work in a distance learning context.

Assessment Development and Validation

While we had a theoretical model of how skill develops and which phase of skill development to focus on, we needed to know precisely what knowledge Marines needed to know, how this knowledge related to shooting performance, and whether this knowledge was malleable (i.e., for applications in future distance learning training applications).

We used the CRESST assessment model to guide assessment development. We focus on identifying the cognitive demands that bear on learning, and these cognitive demands drive the design of the assessment task. The model led us to ask three questions: What are the processes (cognitive, affective, motor) that influence a trainee's successful execution of a task? What are the most direct ways of observing and measuring those processes without the measures altering the measurement itself? and How can these measures be validated to support the inferences drawn from the scores?

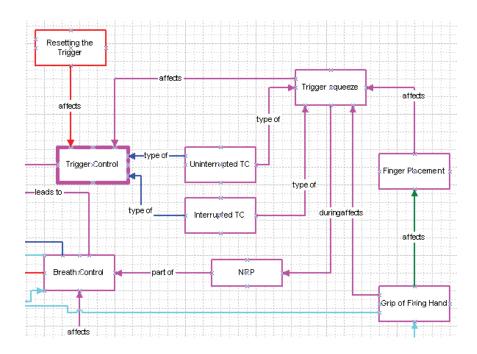
Knowledge Representations

We relied extensively on knowledge representations for practical reasons. Knowledge mapping, a method developed in the writing assessment studies to measure conceptual knowledge (Herl et al., 1996), was used to capture experts' understanding of the domain (Chung, Michiuye, et al., 2002). Experts tend to represent only the most important ideas in a domain, which is an efficient way to identify the major topic areas for an assessment. We also culled from field manuals specific cause-effect relations to augment experts' knowledge maps. The knowledge elements from experts and field manuals were stored in an ontology that was later used for scoring purposes and for instructional purposes.

Capturing Experts' Knowledge

USMC coaches and a scout sniper served as SMEs. Each SME created a knowledge map to represent how they viewed the relations among the various concepts. Figure 2 shows a fragment of the knowledge map. When we overlaid the different experts' maps, it was clear that the most sophisticated map was from a scout sniper. His map spanned multiple areas of marksmanship, reflected what we were learning from SME interviews, and presented an integrated theory of marksmanship. The differences among the various maps were consistent with USMC training, where scout snipers, compared to coaches, receive far more comprehensive and in-depth training on marksmanship.

Figure 2.
Fragment of Experts' Knowledge Maps of Rifle Marksmanship



Measures of Rifle Marksmanship Knowledge

The combination of USMC field manuals (e.g., USMC, 2001), expert interviews, and follow-up discussions with the SMEs made it clear that there was a strong knowledge component to marksmanship in addition to perceptual-motor skills. We organized this knowledge into a framework for rifle marksmanship composed of the following components: cognitive (e.g., domain knowledge), perceptual-motor (aiming, sight picture, fine and gross motor), affective (e.g., anxiety), and equipment and weather.

The set of measures we developed addressed the different components of rifle marksmanship: (a) a broad measure of marksmanship knowledge that sampled the domain and used a selected-response format; (b) a measure of conceptual knowledge using knowledge mapping; (c) an interactive task asking shooters to

identify proper and improper position elements; (d) an interactive task to interpret shot group patterns; and (e) questionnaires to survey trainees' worry, anxiety, and firing line experience. The measures went through multiple reviews by our SMEs.

Validation of Rifle Marksmanship Measures

Empirical validation tested the measures on samples with different levels of experience (non-infantry entry- or sustainment-level Marines and marksmanship coaches; high and low shooting performance) and aptitude (officer candidate school), and on trainees prior to and after instruction. In a series of three studies, we gathered evidence that, in general, suggested that the knowledge measures were sensitive to instruction, predicted record-fire scores moderately in less experienced samples, and when combined with other variables within the skill acquisition framework, predicted record-fire scores as well as scores from a rifle simulator (Chung et al., 2004). We next briefly discuss two interesting measures used in the marksmanship research: knowledge mapping and self-reported worry and anxiety.

While it was clear from the writing assessment studies that knowledge maps could be used to assess conceptual knowledge, knowledge maps were never used in a military training context. As in Herl et al. (1996), experts' maps were used as criterion maps against which trainee maps were scored. We found knowledge maps were sensitive to instruction and sensitive to expertise. Marines' knowledge map scores increased over the course of instruction (Chung et al., 2004, Study 2, 3) and Marines with more marksmanship experience scored higher than those with less experience (Chung et al., 2004, Study 2). These results are consistent with other studies that tested knowledge maps for instructional sensitivity and expertnovice differences (e.g., Herl et al., 1996, 1999; Ruiz-Primo et al., 2001).

The role of anxiety on marksmanship performance was recognized over 100 years ago. Gates (1918) reported that novice shooters' performance was affected severely by their dwelling on steadiness factors (e.g., uttering "There, I moved again"; p. 3). In our studies, the state measures of worry and anxiety administered on qualification day were among the highest predictors of record-fire score, with state anxiety and worry significantly and negatively correlating with record-fire scores (rs ranging from -.4 to -.5) (Chung et al., 2004, Study 2; 2005). Furthermore, when we tested the joint effects of aptitude and state worry inspired by Ackerman's (1987, 1992) study of how aptitude influences performance during the learning

phase, we found that aptitude and state worry predicted record-fire scores with a multiple *R* of .67, with state worry accounting for 34% of the variance and aptitude accounting for 11% (Chung et al., 2005).

Using Assessment to Improve Learning

Because one of our requirements was to develop assessments for a distance learning context, we anticipated the need to demonstrate how assessment information could be used for training purposes. Thus, we developed several methodologies to support future distance learning training applications given the widespread interest in the military in individualizing instruction (Bewley et al., 2009). One of the most important methodologies was the use of knowledge representations or ontologies. An ontology is domain knowledge expressed as a set of concepts and the relations that hold among the concepts (Baker, 2012; Chung et al., 2003; Gruber, 1995). Because ontologies are machine-readable and structured, software can be developed to operate on them. In our case, we created an ontology to represent marksmanship knowledge and linked instructional content in the form of text, figures, and video snippets from USMC training videos to a marksmanship concept (Chung et al., 2004). We then tested on a small sample whether individualizing instruction was effective. The results suggested that Marines receiving individualized instruction improved on topics where they initially had a knowledge gap and not on concepts they did not receive instruction on. The study strongly suggested that the methods used to model knowledge, assess knowledge, and tailor instruction were promising (Chung et al., 2003).

While we could measure one's knowledge of how to carry out a procedure (e.g., trigger control), we had no way to directly measure the execution of that skill. Our follow-on marksmanship R&D work, funded by the Defense Advanced Research Projects Agency (DARPA) investigated whether we could accelerate the acquisition of marksmanship skills. We used sensors to gather information on the difficult-to-observe processes of breath control, trigger control, and muzzle wobble (Espinosa et al., 2009; Nagashima et al., 2009) and we used an observation checklist of the various position elements considered important by experts and USMC doctrine. We tested whether we could use these fine-grained measures to (a) diagnose the novice participants' shooting problems and (b) provide effective individualized remediation using brief video-based instruction. We modeled experts' shots using the sensor data and were able to classify each

shot as expert-like or not (Nagashima et al., 2009). We found that participants who received tailored remediation significantly outperformed those who did not receive tailored instruction, with an average of 2.0 (out of 5) expert-like shots (vs. 1.0 expert-like shots). While this result may seem minor, improving novices' ability to better execute a complex skill composed of cognitive, affective, and perceptual-motor factors in 65 minutes suggested a potentially efficient approach (Chung et al., 2008).

Impact

The idea that rifle marksmanship comprises cognitive, affective, and perceptual-motor factors was novel at the time. The notion that marksmanship has a cognitive component and is a complex skill appears to be accepted by researchers worldwide as evidenced by citations to our work. The insight that marksmanship had a cognitive component was a natural development given CRESST's approach to assessment design best exemplified by Baker's (1974, 1997, 2007) focus on cognition and validity. By grounding the measurement effort around cognition and skill development, new insights were gained about which kinds of assessments would be appropriate for trainees depending on their skill development. This tailoring of measures and content was carried into instructional applications in math (e.g., Chung, Delacruz, et al., 2016), further demonstrating the utility and generality of focusing on cognitive demands first and foremost.

The second impact was the tools and methods developed or applied during the course of the research. Capturing SMEs' knowledge representation served as a method to distill the most important ideas of a domain and a way to assess learners' conceptual knowledge. The use of hardware sensors for measurement purposes would continue (e.g., Chung et al., 2021), and the conceptual and practical connection between measurement and instruction would continue to influence CRESST's technology-based R&D.

Evaluation of Artificial Intelligence (AI) Systems

Al is now at the center of attention in learning technology. We will describe a series of encounters with Al-based systems, for the most part seeking to evaluate their effectiveness. Many studies resulted in a lack of definitive findings because of the limited power of early interventions. Nonetheless, early in CRESST's history, we began numerous studies of advanced technologies, using relatively primitive implementations to explore and evaluate consequences (Baker, 1988). The story of our evaluations of artificial intelligence (Al) systems includes a few pieces. A significant note is that our work was ahead of its time; that is, it stood apart from the usual technology studies in its oddness. Only now, as Al has penetrated the daily lives of many users, our ancient studies are of renewed interest. Our evaluations included early games and simulations, expert systems and models used to support natural language processing and vision systems, and intelligent tutoring systems to promote learning. An important side effect which we will describe is our use of aspects of intelligent system design to enhance our design and implementation of assessments.

Al Games, Simulations, and Intelligent Tutoring Systems

The first game we evaluated using AI was WEST, derived from How the West Was Won, and created by Richard Burton and John Seeley Brown (Burton & Brown, 1979), titans in the early development of AI. Fascinated by the early efforts in this area, CRESST obtained support from NASA to conduct the evaluation of the game along with the Jet Propulsion Laboratory. The principal AI option in the game was a coach which was to support students' learning. We dismantled the coach, and our experiment included students who were exposed to the game with and without the coach support. The findings did not support the utility of the coach.

A second effort was supported by DARPA and was two-pronged. One set of activities was to evaluate AI-based approaches to support former service members who were afflicted with post-traumatic stress disorder (PTSD). A few private companies had created options that could be accessed through smartphones and from periods of activity and other everyday behaviors could infer episodes of PTSD and then implement support. The difficulty with this approach was that it required long periods of use as well as permissions by the users for analyses of their daily technology use. The evaluation design and beginning implementation were carried

out, but the project eventually drew no conclusions because of few users who participated for the desired length of commitment (Baker et al., 2015).

The DARPA game study ENGAGE involved the evaluation of a game developed at Carnegie Mellon University. The game was developed for primary-school-aged learners and taught children to use an adaptation of balance scales to reach conclusions about equivalence (Aleven et al., 2013). Our major evaluation finding was that games could increase the self-efficacy of young learners in the topical subject matter (Baker, 2015; Baker et al., 2016).

As part of this work, CRESST developed its own game focused on physics for 6-year-olds. The game taught concepts of mass, acceleration, and friction, where students needed to manipulate the variables to allow a train to exactly reach its station. In addition, students were to deal with bullying that occurred among characters in the game. Again, limitations of the obtained data interfered with our inferences of effectiveness. We were able to implement and further develop a framework for the evaluation of games that included cognitive demands, domain knowledge, and detailed specifications (Baker et al., 2011; Baker & Delacruz, 2016). Moreover, in developing the scenarios for the physics game, we evolved an assessment design strategy useful for creating exchangeable performance assessments efficiently. The approach created "slots" for key variables in content, task, cognitive demand, and situation that allowed the generation of comparable tasks quickly and at low cost (Baker & Delacruz, 2008).

Simulations

One outcome of our R&D around the evaluation of simulations was the development of novel measures and approaches. Simulations provide learners with experiences that might not be feasible in a classroom or training setting. The simulations CRESST evaluated required learners to engage in problemsolving and reasoning, which also meant the need for measures that would be sensitive to these higher level learning outcomes.

A persistent design goal was to measure the phenomenon in as direct a way as possible. This objective pushed R&D developments in three areas: first, to continue to apply the CRESST model of assessment, which maintained our attention on how cognitive demands of the simulation task related to the assessment task design; second, to adopt or develop measures that reflected the productive (or

nonproductive) uses of the unique learning affordances of the simulations; and third, to instrument our evaluation tools to capture and log fine-grained learner-system interactions (also called log data, trace data, or clickstream) and to use those data for assessment purposes.

Evaluating Content Understanding and Problem-Solving

Beginning in the mid-1990s, we began to explore how simulations could be used for assessment purposes. We became increasingly confident over several studies that simulations that required performance demonstrations could also be used for assessment purposes. For example, we developed a simulated web environment to evaluate middle-school students' content understanding and problem-solving. Content understanding was measured with knowledge maps, and problem-solving was measured by information seeking and search (Baker & Mayer, 1999). The educational setting was the Department of Defense Education Activity (DoDEA) middle schools in Germany, where large investments in computer-aided educational tools were introduced into the schools. The study found students' search skills and knowledge of environmental science significantly improved from the fall to spring semesters and knowledge map scores were significantly related with the quality of their search behavior (rs from .4 to .5) (Schacter et al., 1999).

This study was foundational in that we demonstrated the technical feasibility of collecting fine-grained behavioral process data and showed that students' online behavior was related to their content understanding and problem-solving outcomes. The capability to link students' behavior to their improved knowledge led to an obvious understanding: If students attended to the relevant content, they would learn that content. While a simplistic insight and long known in the verbal memory research, this finding was with an educationally relevant task where we could directly tie learners' behavior to the to-be-learned content. The challenge was not in the technology development or instrumentation, but rather in being able to create tasks where the learner interaction was aligned with the cognitive demands that influenced outcome performance. We concluded that under this situation, behavioral process data could be highly informative.

Given the promising results of the web search study, we then examined another simulation to gather validity evidence of the degree to which learners' online behavior reflected their cognitive processes. This linkage was important to establish because there was scant evidence in the literature to confirm that

learners' online behaviors were representations of their thinking. Establishing such a link would increase our confidence in the use of online behavior as a source of evidence about learning processes. Chung et al. (2002) collected process data and concurrent think-alouds from students as they engaged in a web-based problem-solving simulation task. The simulation required learners to determine the parents of five children (Stevens et al., 1999). The learners could access information sources with different credibility (e.g., genetic lab test results, opinions of people, library) to rule out candidate parents.

Similar to the web search results (Schacter et al., 1999), task performance was significantly and positively related to learners' fine-grained behavior reflecting the use of credible sources and negatively related to use of non-credible sources. We also confirmed that productive cognitive processes (based on students' thinkalouds) were significantly related to existing validated measures of reasoning. When we examined how learners' cognitive processes were related to their online behaviors, we found that productive cognitive processing was significantly associated with task performance and productive learner behaviors and vice versa, with the magnitude of correlations in the .5 to .7 range. The results of triangulating cognitive processes derived from think-alouds, validated measures of reasoning, and learners' behaviors bolstered considerably our confidence in the use of online behavioral data for measurement purposes (Chung, de Vries, et al., 2002).

The final simulation example addressed the extent to which a simulation designed specifically for training purposes could be used for assessment purposes (Iseli et al., 2019; Savitsky, 2013). For this study, CRESST developed and validated methods to assess both declarative and procedural skills for two ultrasound-guided procedures taught in the simulator. Declarative knowledge was measured by a general test of knowledge of the two ultrasound procedures. Procedural knowledge was measured by the quality of sonographers' ultrasound scanning with a probe. The probe-motion measures were derived from moment-to-moment telemetry of the pitch, yaw, and roll of the probe. We found that more experienced sonographers demonstrated superior overall task performance and probe manipulation skills compared to less experienced sonographers, with effect sizes between the two groups of participants ranging from 0.2 to 2.0 across the various probe-based measures. These results, coupled with the marksmanship study involving sensors, suggested that the data from hardware sensers could be used in similar ways as we were using online behavior data. These results also suggested

a kind of generality: The utility of learner behavioral data is less about the specific source (software or hardware) and much more about whether the behavior is a manifestation of cognitive processes of interest.

A major theme of our simulation evaluation examples is the use of the CRESST assessment model. In every study, the learner and learning outcomes were the focus of the assessment task design effort. The cognitive demands required of the task, and in particular the unique aspects of the simulation task, guided the development of novel assessments that measured as directly as possible the presumed learning outcomes and processes. The close attention to cognitive demands and how they manifest in learners in a given task design also led to insights about which kinds of behavior in the simulation carried information related to learning and which did not. These insights would be carried into future work on game-based learning and game-based measurement.

Intelligent Tutoring Systems (ITS)

One of the most common and early uses of AI was its application to intelligent systems for learning. Early called intelligent computer assisted instruction (ICAI), several studies were conducted by CRESST (O'Neil & Baker, 1987). About two decades later these inquiries continued, supported by the Office of Naval Research (Kumar et al., 2015; VanLehn et al., 2016). In this section, instead of presenting a full example of an ITS evaluation, we present an example of measures development, a key issue when evaluating systems that individualize instruction.

The results of any evaluation rest on the quality of the outcome and process measures. ITS presents a special case because the instruction tends to be individualized, and system instructional decisions are made using granular data (e.g., presenting feedback tailored to a specific type of learner response). Thus, a challenge posed by ITSs (and systems that individualize instruction) is determining effectiveness when different students receive different degrees of content exposure, practice, and feedback.

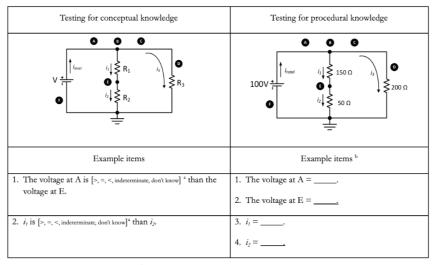
The approach we used focused on the precision of measurement. Because an ITS often attempts to remediate knowledge gaps on specific topics (e.g., understanding how to compute the equivalent resistance of three resistors in parallel), we reasoned that the measures used in evaluating the ITS should also match the precision of the instruction as a broader outcome measure might not

detect very narrow effects. One example of this approach was the evaluation of the ITS *LearnForm* (Kumar et al., 2015). *LearnForm* was an ITS problem-solving environment where students were first presented with a selected-response item. If they answered the item incorrectly, they could receive step-by-step, granular instruction and practice on the underlying topics related to the test item. The system's evaluation focused on electric circuits in AP Physics classrooms.

The measures development consisted of a physics SME first developing an ontology of electric circuits to identify the important domain concepts. These concepts were decomposed into specific knowledge components. Item development involved reviewing the electric circuit literature for misconceptions, developing canonical circuit topologies, and evaluating candidate items against the set of knowledge components.

Successful analysis of a circuit requires the simultaneous consideration of the relations among voltage, current, and resistance. To mirror this cognitive demand, we adapted an item format from Richardson et al. (1933, p. 55) and discussed in Haladyna and Rodriguez (2013). As shown in Figure 3, the item was used to assess conceptual understanding of the relations among current, voltage, and resistance, and procedural knowledge of how to apply Ohm's Law to compute voltage and current.

Figure 3.
Example Conceptual and Procedural Knowledge Items



^a Participants select one option. ^b Participants compute the answer.

The format shown in Figure 3 allowed us to create seven scales with 41 items. The scales underwent multiple rounds of review and validation testing. The internal reliability of the scales (Cronbach's alphas) ranged from 0.7 to 0.8 (Chung, Madni, et al., 2014). Knowledge sensitivity was verified by comparing electrical engineering (EE) students to a general sample, where EE students performed significantly higher than the general sample. Instructional sensitivity of the scales was verified by first showing that the EE sample did not change over instruction (i.e., no difference in pretest and posttest scores), and also showing that scores increased from pretest to posttest in the general sample (*ds* ranging from 0.3 to 0.5). *LearnForm* effectiveness was demonstrated with an evaluation sample that improved from pretest to posttest on the scales (*ds* ranging from 0.7 to 1.9), and by demonstrating that learners who received the step-by-step instruction outperformed those who could opt out of the step-by-step instruction on the conceptual circuit analysis measure (*d* = 0.8) (Chung et al., 2015).

Human Benchmarking of AI Systems

DARPA supported an innovative set of studies evaluating early AI systems using human performance as the guide (Baker & Butler, 1991; Swigger et al., 1990). These systems included an example of natural language processing (NLP), a completed expert system in the area of scheduling, a vision system (Baker et al., 1988), and an expert systems shell. The project was initially and deliberately controversial in the computer science area, because the principal investigator was not a computer scientist. However, the evaluators of each major component came from the computer science domain. The question posed in this study was how well the system performed in comparison to human performance. Common tasks for humans were transformed and were acted upon by systems and then levels of performance were inferred. For instance, early evidence from NLP systems suggested at that time, performance was like that of a primary-school-aged child (Baker, 1994). For the most part, the work was conducted, albeit with interruptions from the funding agency when the initial supporter changed agencies. In the expert system scheduling analysis, systems managing scheduling of airplanes to gates existed, and similar tasks were given to people (O'Neil et al., 1994). Reports of this work were developed and form some of the basis of current studies of system predeveloped problem sets to evaluate comparatively the efficiency and growth of distributed systems such as ChatGPT (Baker, 1989; Baker et al., 2025).

Impact

To understand the implications of our early work in evaluating AI, two conditions are clear. One is that early formulations were extremely limited in design, and so were the evaluation options open to CRESST. To this day, CRESST is continuing to engage with AI options to support our own work in the design of ontologies and performance assessments for learning, to develop measures for various types of data collection, to explore the use of intelligent agents to act as simulated students for assessment and evaluation, and to attempt to understand what learning quality means in the era of expanding machine intelligence.

Game-Based Learning and Assessment

In this section, we present selected examples, findings, and insights from our R&D portfolio around games for learning and assessment. While the examples are drawn from our work sponsored by the U.S. Department of Education (ED), the Institute of Education Sciences (IES), and PBS KIDS, many of the methodologies and lessons learned were the result of continuous cross-fertilization among the various ongoing military games and simulation programs at CRESST sponsored by the Office of Naval Research (e.g., Baker & O'Neil, 2002; Iseli & Jha, 2016; Iseli et al., 2010; Koenig et al., 2010), DARPA (e.g., Baker et al., 2012; Baker & Delacruz, 2016; Madni et al., 2013; O'Neil et al., 2021), California Department of Education (e.g., Chung et al., 2018), private foundations (e.g., Chung, de Vries, et al., 2002), and start-up organizations (e.g., Ihlenfeldt et al., 2025).

Game-Based Learning

In 2009, CRESST was awarded a multimillion-dollar 5-year national R&D center on instructional technology grant from the U.S. Department of Education, Institute of Education Sciences (IES). The center, named the Center for Advanced Technology in Schools (CATS), developed and tested fractions math games for underperforming middle-school students in a cluster randomized controlled trial (RCT). The RCT involved 23 schools, 59 classrooms, and 1,468 students and demonstrated that students who played four fractions games performed higher on a test of fractions knowledge, compared to the comparison group who played four solving equations games (d = 0.23) (CATS, 2012; Chung et al., 2014; ED, IES, WWC, 2015). We next highlight several innovative aspects of CATS: coherent design process, game as testbed, gameplay as a data source, and advanced statistical modeling.

Coherent Design Process

We used the CRESST assessment model (Baker, 1997, 2007) to develop knowledge specifications. Ontologies were used to describe the major concepts and relations in the content domains (Baker, 2012) and the knowledge specifications succinctly described the target concepts, types of stimuli to elicit student responses, and performance expectations. The knowledge specifications standardized the requirements for assessment design, game design, and professional development for the target domains (rational number equivalence, CATS, 2013b; solving equations, CATS, 2013c; functions, CATS, 2013a). A fragment of the knowledge specification for rational number equivalence is shown in Figure 4.

Figure 4.
Snippet of Knowledge Specifications for Rational Number Equivalence

	Computational Fluency: Students can execute procedures in the domain without the need to create or derive the procedure. Fluid performance is based on recall of patterns or other well established procedures, and is fast, automatic, and error-free. How is something done?		Conceptual Understanding: Captures demonstration of understanding of the mathematical concepts. Why is something done?	
Rational Number Equivalence Knowledge	When presented with	Students should be able	When presented with	Students should be able
Specifications	(Assessment Stimulus)	to	(Assessment Stimulus)	to
1.0.0. Does the student understand the				
importance of the unit whole or amount?				
1.1.0. The size of a rational number is relative to how one Whole Unit is	Any rational number	Place it on a number line relative to the whole interval explicitly (0 and 1 labeled) or implicitly (0 and an integer other than 1 labeled) defined.	Apparent contradictions involving rational number such as 1/4 < 1/2 or 1/2 does not equal 1/2	Explain that the contradiction can be resolved if their relative wholes must be equal when comparing.
defined.	A unit whole (interval, volume, area, etc.)	Show how much of the whole must be shaded to represent a fractional amount.		

All assessments, games and game levels, and professional development were designed against the knowledge specifications. Both the game levels and assessment items were mapped to the knowledge specifications, allowing verification of adequate domain coverage and alignment between the instruction, the game levels, and the assessment.

Game Testbed to Accelerate Research

A second innovation that enabled CRESST to conduct 17 design studies over two years was to design the games as a testbed. All games were designed to allow researchers to specify the level design using a text file instead of needing a programmer to program the levels. For example, in the game *Save Patch*, if a player failed the level, researchers could specify instruction or feedback tailored for the first failure, second failure, and so on, and also specify that the instruction be delivered in different modalities (e.g., text only, video). An example of the utility of the testbed was in simply modifying five text files to create five versions of *Save Patch* to identify the most promising forms of feedback to implement in the games used in the RCT (Vendlinski et al., 2011).

Gameplay as a Data Source

A third innovation was the use of fine-grained telemetry for measurement purposes. Our prior work with process data (Chung, de Vries, et al., 2002; Schacter et al., 1999) guided our telemetry design of what game mechanics to instrument, what game states to record, how to structure the data, and how to format and log the data. Yet we were unsure whether gameplay itself carried information about

learning as game-based learning was an emerging field at the time. While our first three experimental studies did not show outcome differences due to instructional variations, we did find significant gains over gameplay (*ds* from .3 to .4), hinting that the game design and game mechanics were effective in conveying the fractions concepts (Chung et al., 2010). We found that players receiving math-focused instruction (vs. game-focused instruction) generally committed fewer errors in the game that were related to math (*ds* from 0.3 to 0.5), and the math posttest was significantly related to gameplay behaviors reflecting successful fraction addition (*rs* from 0.3 to 0.6) and negatively related to gameplay behaviors reflecting unsuccessful fraction addition (*rs* around -.3). These results suggested that gameplay behavior itself carried information about learners' fractions knowledge.

These results were generally replicated in subsequent studies, suggesting that the game facilitated learners' acquisition of fractions knowledge (Vendlinski et al., 2011). Furthermore, the pattern of how gameplay related to tests of knowledge repeatedly showed that knowledge was positively related to productive gameplay behavior and negatively related to unproductive gameplay behavior, consistent with prior work (Chung & Baker, 2003; Chung, de Vries, et al., 2002; Schacter et al., 1999). These results spurred continued examination of the use of process data, including using data mining methods to detect misconceptions (e.g., Kerr, 2014; Kerr & Chung, 2012a, 2012b, 2013b), to test whether instructional variations affected specific gameplay behaviors (Buschang et al., 2012; Chung et al., 2010), to identify different learning trajectories (Kerr & Chung, 2013a), to model diagnostic assessments (Levy, 2019), and to extract best practices and guidelines on the design of telemetry (Chung, 2015). The quality of the telemetry data and RCT design, coherent game design, and external measures have led to researchers continuing to use the CATS RCT dataset to develop and explore new methods for process data analysis (Feng & Cai, 2024, 2025; Tadayon & Pottie, 2020).

Advanced Statistical Modeling

A fourth innovation was the advancement of methodology relevant to large-scale educational effectiveness studies. Cai et al. (2016) developed a novel way to account for many of the constraints inherent in multisite RCT study designs. Using the CATS RCT data, Cai et al. accounted for the RCT design constraints by using a multilevel two-tier item factor model to model latent gain. Cai et al.'s method was more precise in estimating effectiveness by being able to isolate the part of the posttest variance that was sensitive to change. The resulting effect size of d=0.57

was more than twice the magnitude of the effect size computed for CATS using a classical measurement approach (d = 0.23) and used by WWC in its reviews of educational intervention studies (ED, IES, WWC, 2015).

Game-Based Assessment

The potential of using games for assessment purposes has been of interest to the measurement and assessment communities for some time (for a discussion of these issues related to games, see Baker et al., 2011; Baker & Delacruz, 2008, 2016; Delacruz, 2011; DiCerbo et al., 2016; Landers, 2015; Mislevy et al., 2015; Oranje et al., 2019; OECD, 2014, 2021; Shute & Wang, 2016; Sireci, 2016; for a discussion of these issues related to process data in assessments, see Jiao et al., 2021; Lindner & Greiff, 2023; Zumbo et al., 2023). A common aspirational goal is to "replace the dull, time-consuming, and anxiety-producing traditional approaches commonly used today" (Landers, 2015, p. vii). Landers's sentiment reflects the general desire to develop other means of measuring what learners know and can do under more engaging and complex situations.

While there may be much interest in using games for assessment purposes, numerous literature reviews have found few studies that gathered validity evidence about how games in general and game mechanics in particular relate to knowledge, skills, and learning processes (Chung & Feng, 2024; see reviews by Gómez et al., 2022; Gris & Bengtson, 2021; Kim & Ifenthaler, 2019; Tlili et al., 2021; Wiley et al., 2021). In the remainder of this section, we describe some of the R&D related to gathering such validity evidence.

Identification of Game Features That Facilitate Measurement

One of the continuous efforts in CRESST's games-related R&D has been to identify game features to support measurement. The features were identified through usability studies, qualitative feature analysis, repeated observation of similar patterns of results, and data cleaning and algorithm development. A set of the most important features are described next.

When considering a game for measurement purposes, we think the most important game feature is the alignment among the game design, game mechanics, cognitive demands evoked by the game, and the external measure used to measure the learning outcomes of the game (Baker et al., 2011; Baker & Delacruz, 2008, 2016). For example, if a game is intended to promote computational thinking, then the

gameplay should require learners to engage in the critical computational thinking processes of designing a solution, failing, debugging, and iteration. A game that minimizes learner failures and errors will not be able to detect gaps in knowledge or the presence of misconceptions because players will have few opportunities to make mistakes.

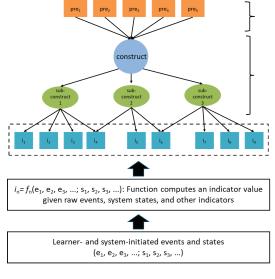
The underlying idea is that the only possible observable behaviors are the interactions the game permits. If understanding the full range of learner performance is important, then having the complement of understanding—not understanding as exhibited by errors and misconceptions—is extremely valuable because measures of success and measures of failure can provide converging validity evidence. More generally, learners with higher domain knowledge should demonstrate more productive behaviors and fewer unproductive behaviors, and learners with lower domain knowledge should demonstrate the opposite relations. We have consistently observed these complementary relations when tasks are tightly aligned with the external measures of domain knowledge (e.g., Chung & Feng, 2024).

A second important game feature is practical. The user interface (UI) imposes constraints on learners' behavior (Chung & Baker, 2003). An important consideration is how to ensure that an action is intentional and not a mistake or other unwanted behavior that would contribute to construct-irrelevant variance. One type of UI element is the use of an explicit click (e.g., a button or similar UI element) that allows learners to signal, for example, that they are ready to move to the next level, to test a potential solution to a design, to select one option from a set of options, or to request help. Cleverly designed game mechanics can allow learners to perform such explicit actions as a natural part of the game. An explicit action also marks data and simplifies algorithm development by having explicit markers in the data to delineate time windows, sequences, and different levels of aggregation. Finally, game mechanics that require learners to render a judgment related to the content are especially useful if their choices can be evaluated (e.g., if moving a game piece can be evaluated as a correct or incorrect action).

Figure 5 shows how we think about fine-grained gameplay behavior (i.e., raw telemetry), indicators, and a measurement model. Indicator development often requires extensive data cleaning and processing to transform moment-to-moment events into inputs to statistical models. The programming task can range from

simply counting events to deriving numerous auxiliary variables to represent different game states that are themselves used to derive indicators. The encoding of useful information in the telemetry is dependent on both what the game allows learners to do through game mechanics, and the degree to which the game mechanics reflect the desired cognitive demands.

Figure 5.
Computational Modeling Conceptualization



STUDENT BKGND LAYER

- Prior knowledge, programming experience
- Age, sex, language proficiency

CONSTRUCT LAYER

Construct, subordinate constructs, and inter-dependencies

INDICATOR LAYER

Behavioral evidence of construct.

TRANSFORMATION FUNCTION LAYER

Algorithms developed to process raw telemetry to derive atomic and auxiliary indicators.

EVENT LAYER (RAW TELEMETRY)

Learner behavior and system events and states. May include atomic indicators.

Validity Evidence

Chung and Feng (2024) addressed the question, *To what extent do game-based indicators relate to criterion measures of learning*? drawing on various CRESST game-related studies. The authors reported that "common measures" composed of game performance and game progress indicators appear sensitive to the criterion measure across a broad set of games (See Chung & Feng, Appendix). The definition of game progress and game performance are game independent and analogous to the speed and accuracy variables studied extensively in verbal learning and motor learning. One use of game progress and game performance variables might also serve as a standardized metric to compare learning games

on their potential to promote knowledge or skill. See Chung and Feng (2024) and Chung and Roberts (2018) for additional examples.

The second type of indicators are game-specific indicators tailored to a game. For example, indicators of debugging behaviors were developed for a programming game (Feng & Chung, 2022), misconceptions developed for a pan balance game (Feng, 2019), deductive reasoning for a problem-solving game (Chung et al., 2018), and fractions misconceptions for a fractions game (Kerr, 2014). In all cases, the relation between the indicators and an external outcome measure were in the expected directions. Indicators that represent productive behaviors were often significantly and positively related to the external criterion measure, and indicators representing unproductive behavior were often significantly and *negatively* related to the external criterion measure (additional examples are presented in Choi, Parks, et al., 2021; Chung & Feng, 2024; Chung & Parks, 2015; Chung, Parks, et al., 2016; Redman et al., 2018, 2020, 2021, 2025; Roberts et al., 2016).

Application of Psychometric Modeling to Gameplay Data

One of the most important advances in game-based assessment was demonstrated by Feng and Cai (2024). In their study, the authors used the CATS RCT dataset to jointly model pretest, posttest, and gameplay data using a cross-classified IRT model. Feng and Cai modeled learners' latent changes in fractions knowledge and were able to directly relate the latent change to gameplay behavior. This new modeling approach directly provides information often of most interest in educational interventions: How much did learners learn (as described by latent changes in learners' knowledge over the course of instruction), and what variables influenced their learning (as described by learners' gameplay behavior)? Furthermore, the modeling technique is sufficiently general to incorporate other streams of data, such as multimodal data (e.g., eye tracking), learner background information, level design information, and interactions between learners' characteristics and the instructional setting.

Use of Population Data

One challenge presented by PBS KIDS (See Roberts et al., in press) was to examine how games played "in the wild" (i.e., the population) can be used to understand PBS KIDS' audience better. The only information available with population gameplay data is an anonymous ID. Three general issues were explored: using

psychometric modeling to estimate latent ability, using population-derived models and parameters in RCT studies, and testing a method to infer learning solely from players' gameplay behavior.

Psychometric Modeling of Population Gameplay Data

In numerous studies involving PBS KIDS' gameplay data from players "in the wild," CRESST applied various psychometric models. A close analysis of the game design and available gameplay indicators dictated the choice of models. The models included higher order IRT (de la Torre & Song, 2009) and diagnostic classification (Rupp et al., 2010) in Choi, Suh, et al. (2021); Rasch and Rasch Poisson counts (Rasch, 1960), IRT trees, and linear logistic testing model (De Boeck & Wilson, 2004) in Redman et al. (2021); a one-factor 2PL model, bifactor 2PL model with two and three specific factors in Redman et al. (2023); a multiple-group two-time point nominal IRT model (Cai, 2010; Cai & Houts, 2021) in Redman et al. (2025); and a two-time point graded response IRT model in Feng et al. (2025).

Using Population Information in RCT Studies.

To demonstrate how population data could be used in RCT studies, Choi, Parks, et al. (2021) used population gameplay to fit higher order IRT models for two PBS KIDS games. Choi, Suh, et al. (2021) used the population-based models and estimated model parameters from Choi, Parks, et al. (2021) to estimate ability of learners playing the same games in an RCT sample (Education Development Center, Inc., & SRI International, 2021). Diagnostic classification models (DCM) were also used to estimate informational text attribute profiles in both the RCT sample and population.

Estimating Learning in the Population Through Gameplay.

Finally, we explored the use of PBS KIDS games played "in the wild" to directly measure changes in gameplay that were consistent with changes in learning (Redman et al., 2023). The games were classified into three categories (likely, less likely, not likely) on their potential to promote learning. A two-timepoint latent variable model was used to estimate changes in latent ability using only gamebased indicators. The study found that for the two games rated as not likely or less likely to result in learning, the effect sizes of the change in latent score were 0.07. In contrast, for the two games that were rated as likely to result in learning, the effect sizes of the change in latent score were 0.56 and 0.59.

Impact

The breadth of CRESST R&D around games for learning and games for assessment have led to insights about the conditions needed for both learning and measurement to be realized: Games that are effective in promoting learning can also yield information about learners' knowledge and skills, but only if (a) the game design and game mechanics in particular evoke the intended cognitive demands, (b) the game is instrumented to collect moment-to-moment telemetry and game state information, (c) the algorithms used to derive indicators from the telemetry are able to represent a range of performance, and (d) the psychometric models account for the constraints imposed by the game itself.

An important implication of this work for AISL is the idea of *measurement without testing*. Regardless of the type of task—game or otherwise—if the learner's behavior in the task is a manifestation of the desired cognitive demand, then the learner's behavior can serve as evidence of the cognitive demand occurring. This idea holds regardless of whether a task is designed for testing purposes or for learning purposes, for it is the interaction that is the atomic unit of observation.

Conclusion

This chapter presented a few examples of CRESST research extending over several years of effort and gave only a handful of references for each of them. Every area includes the importance of designing assessments to map to the purpose of evaluation and to provide as much transparency as possible. In most cases, our evaluations addressed not only performance on outcomes, but the value of instructional procedures and learner processes as well.

CRESST did not always juggle well the competing goals of innovation and early involvement with longer term impact. Much of our work was, in a self-aggrandizing sense, ahead of its time. This lack of fit with the context of learning and assessment vastly limited its immediate impact. However, we want to acknowledge and thank those educational and technology leaders who joined with us to explore learning and assessment strategies that were often too early for widespread use. There are numerous examples of other CRESST activities that affected proximal practice. The selection we chose to highlight, however, are focused on ideas that continue to affect educational research and development.

The methodologies and insights described in the examples also foreshadow the movement toward AISL, most clearly seen in the focus, since the inception of CRESST, on exploring assessment in the context of learning to support both attainment of learning goals and as an outcome measure. As the examples illustrate, designing assessments in the context of learning:

- Emphasizes measuring the most important concepts and skills.
- Conceives of human performance as being on a continuum, which naturally leads to the choice of experts as the criterion or reference against which to judge learner performance.
- Situates cognitive demands as a core assessment design requirement. By specifying and unpacking the key learning processes and outcomes a task is expected to evoke from learners, the assessment design process can be focused. Clear specifications can guide the development of measures, instructional content, and professional development.
- Treats the quality of measures as a necessary condition for drawing valid inferences by having clear and comprehensive definitions of what is to be measured, by making explicit how a student response is transformed into a quantitative value, and gathering validity evidence that the measures behave in expected ways.
- Is agnostic on the instructional or assessment setting, as well as the media, mode, and format used for instruction or assessment. Paper, digital, selectedresponse or constructed-response modes and formats can provide different information under different situations.
- Does not preclude a learning task from providing measurement information. A
 learning task can provide information about learners' ongoing knowledge and
 skills if learners are able to actually engage in the target cognitive demands and
 if learners' behaviors can be captured and stored.

As the assessment enterprise moves increasingly toward AISL, we think CRESST's experience can shed light on some of the challenges and opportunities ahead. The most important challenge is an understanding of cognitive demands and its implications for task design, the types and range of learner responses evoked by the task, and data capture opportunities. Additionally, adopting a naive view of measurement may be helpful for alignment, especially in technology-based

environments. If we think of the initial stages of measurement as simply an observation with some quantitative value assigned to it, then we can view a task as a set of learner-system interactions. Most of the interactions will be of little interest, but interactions that reflect judgment, decision making, or application of the target knowledge can be highly informative because they presumably reflect the outputs of learners' knowledge and skill. Furthermore, these interactions can be thought of as atomic units that can be combined, sequenced, or aggregated to form indicators that match future claims and inferences. Finally, this conceptualization, used in our work in simulations and games, can be applied to any environment where interactions exist. The limiting factor is observational capability.

The examples in this chapter addressed the Handbook principles of *transparency*, *purpose* and *focus*, and *validity*. As the field moves to more technology-based solutions, we think these principles become even more salient. Complex technology often obfuscates what is actually happening "under the hood" making independent inspection and critique nearly impossible. One path to make such systems more transparent is to develop tools and methods to specify in a formal way what to measure and the rules for transforming an observation into a measure. Another path is the training of assessment designers and technology developers on the AISL principles, methodologies, and insights described in this chapter so that best practices are designed into the applications. Regardless of approach, we are confident that AISL can be realized.

References

- Ackerman, P. L. (1987). Individual differences in skill learning: An integration of psychometric and information processing perspectives. *Psychological Bulletin*, 102, 3–27.
- Ackerman, P. L. (1992). Predicting individual differences in complex skill acquisition: Dynamics of ability determinants. *Journal of Applied Psychology*, 77, 598–614.
- Aleven, V., Dow, S., Christel, M., Stevens, S., Rosé, C., Koedinger, K., Myers, B., Flynn, J. B., Hintzman, Z., Harpstead, E., Hwang, S., Lomas, D., Reid, C., Yannier, N., Fathollahpour, M., Glenn, A., Sewall, J., Balash, J., Bastida, N., & Zhang, X. (2013). Supporting social-emotional development in collaborative inquiry games for K-3 science learning. In *Proceedings of the 9th Games+ Learning+ Society Conference-GLS* (Vol. 9, pp. 53–60). ETC Press.
- Baker, E. L. (1974). Beyond objectives: Domain-referenced tests for evaluation and instructional improvement. *Educational Technology*, *14*(6), 10–16.
- Baker, E. L. (1981, April 13–17). Issues in the evaluation of composition instruction [Paper presentation]. Annual meeting of the American Educational Research Association, Los Angeles, CA, United States.
- Baker, E. L. (1982). The specification of writing tasks. *Evaluation in Education: An International Review Series*, *5*(3), 291–297.
- Baker, E. L. (1988). Evaluating new technology: Formative evaluation of intelligent computer assisted instruction. In R. J. Seidel & P. D. Weddle (Eds.), *Computer-based instruction in military environments* (pp. 155–162). Plenum Publishing.
- Baker, E. L. (1989, March 27–31). The role of outcome measurement in the development and assessment of Al-based educational systems [Paper presentation]. Annual meeting of the American Educational Research Association, San Francisco, CA, United States.
- Baker, E. L. (1994). Human benchmarking of natural language systems. In H. F. O'Neil & E. L. Baker (Eds.), *Technology assessment of software applications* (pp. 85–98). Erlbaum.

- Baker, E. L. (1997). Model-based performance assessment. *Theory Into Practice*, 36(4), 247–254.
- Baker, E. L. (2007). Model-based assessments to support learning and accountability: The evolution of CRESST's research on multiple-purpose measures. *Educational Assessment* (Special Issue), *12*(3&4), 179–194.
- Baker, E. L. (2012). *Ontology-based educational design: Seeing is believing* (Resource Paper No. 13). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Baker, E. L. (2015). Final report: Gamechanger: Using Technology to Improve Young Children's STEM Learning (Deliverable to funder). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Baker, E. L., Baron, J., Coffman, W., Freedman, S., Quellmalz, E., & Williams, P. (1986, September). *Issues in writing assessment for NAEP* [Paper presentation]. Office of Technology Assessment, Washington, DC.
- Baker, E. L., & Butler, F. A. (1991). Artificial intelligence measurement system: Overview and lessons learned (ED332677). ERIC. https://files.eric.ed.gov/fulltext/ED332677.pdf
- Baker, E. L., Choi, K., & O'Neil, H. F. (2022). The training assessment framework: Innovative tools using scenario-based assessment and feature analysis. In A. M. Sinatra, A. C. Graesser, X. Hu, B. Goldberg, A. J. Hampton, & J. H. Johnston (Eds.), *Design recommendations for intelligent tutoring systems* (pp. 31–39). U.S. Army Combat Capabilities Development Command.
- Baker, E. L., Chung, G. K. W. K., & Delacruz, G. C. (2011). The best and future uses of assessment in games. In *Technology-based assessments for 21st century skills* (pp. 227–246). Information Age Publishing.
- Baker, E. L., Chung, G. K. W. K., Delacruz, G. C., & Griffin, N. C. (2012). *Engage validation plan* (Year 1 Deliverable). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).

- Baker, E. L., Clayton, S., Aschbacher, P., Chang, S., & Ni, Y. (1990, April 16–20).
 Measuring deep understanding of history: The integration of prior knowledge and knowledge acquisition in explanations [Paper presentation]. Annual meeting of the American Educational Research Association, Boston, MA, United States.
- Baker, E. L., & Delacruz, G. C. (2008). A framework for the assessment of learning games. In H. F. O'Neil & R. S. Perez (Eds.), *Computer games and team and individual learning* (pp. 21–37). Elsevier.
- Baker, E. L., & Delacruz, G. (2016). A framework to create effective learning games and simulations. In H. F. O'Neil, R. S. Perez, & E. L. Baker (Eds.), *Using games and simulations for teaching and assessment: Key issues* (pp. 3–20). Routledge/ Taylor & Francis.
- Baker, E. L., Freeman, M., & Clayton, S. (1991). Cognitive assessment of history for large-scale testing. In M. C. Wittrock & E. L. Baker (Eds.), *Testing and cognition* (pp. 131–153). Prentice-Hall.
- Baker, E. L., & Gordon, E. W. (2014). From the assessment OF education to assessment FOR education: Policy and futures. *Teachers College Record*, 116(11), 1–24.
- Baker, E. L., Koenig, A. D., Lee, J. J., Choi, K., O'Neil, H. F., Michiuye, J., K., & Griffin, N. (2025, January 4–7). The Training Assessment Framework project: Flexible design from classroom to AI [Paper presentation]. Annual Hawaii International Conference on Education, Honolulu, HI, United States.
- Baker, E. L., Lee, J. J., Rivera, N. M., Choi, K., Bewley, W. L., Stripling, R., O'Neil, H. F. Jr., & Redman, E. (2015). Detection and computational analysis of psychological signals: Evaluation of digital library and SimSensei for veteran use (Final deliverable to funder). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Baker, E. L., Lindheim, E. L., & Skrzypek, J. (1988). *Directly comparing computer* and human performance in language understanding and visual reasoning (CSE Report 288). University of California, Los Angeles, Center for the Study of Evaluation.

- Baker, E. L., Madni, A., Choi, K., Kim, J., Redman, E. H., Delacruz, G. C., Chung, G. K. W. K., Griffin, N. C., & O'Neil, H. F. (2016). ENGAGE2: Computer games for science learning at early grades: Evaluation, assessment, and neuro-sensing investigation (Deliverable to funder). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Baker, E. L., & Mayer, R. E. (1999). Computer-based assessment of problem solving. *Computers in Human Behavior, 15*(3–4), 269–282.
- Baker, E. L., McGaw, B., & Sutherland, S. (2002). *Maintaining GCE A level standards*. Qualifications and Curriculum Authority.
- Baker, E. L., Niemi, D., Herl, H., Aguirre-Muñoz, Z., Staley, L., Linn, R. L., & Rogosa,
 D. (1996). Report on the content area performance assessments (CAPA):
 A collaboration among the Hawaii Department of Education, the Center for Research on Evaluation, Standards, and Student Testing (CRESST) and the teachers and children of Hawaii (Final Deliverable). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Baker, E. L., & O'Neil, H. F. (2002). Measuring problem solving in computer environments: Current and future states. *Computers in Human Behavior*, *18*(6), 609–622. https://doi.org/10.1016/S0747-5632(02)00019-5
- Baker, E. L., & Quellmalz, E. (1986, March 13–15). *Initial results for the U.S. writing study* [Paper presentation]. Conference on College Communication and Composition, New Orleans, LA, United States.
- Bewley, W. L., Chung, G. K. W. K., Delacruz, G. C., & Baker, E. L. (2009). Assessment models and tools for virtual environment training. In D. Schmorrow, J. Cohn, & D. Nicholson (Eds.), *The PSI handbook of virtual environments for training and education: Developments for the military and beyond* (pp. 300–313). Praeger Security International.
- Burton, R. R., & Brown, J. S. (1979). An investigation of computer coaching for informal learning activities. *International Journal of Man-Machine Studies*, 11(1), 5–24. https://doi.org/10.1016/S0020-7373(79)80003-6

- Buschang, R. E., Kerr, D., & Chung, G. K. W. K. (2012). Examining feedback in an instructional video game using process data and error analysis (CRESST Report 817). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Cai, L. (2010). A two-tier full-information item factor analysis model with applications. *Psychometrika*, *75*, 581–612.
- Cai, L., & Houts, C. R. (2021). Longitudinal analysis of patient-reported outcomes in clinical trials: Applications of multilevel and multi-dimensional item response theory. *Psychometrika*, *86*, 754–777.
- Cai, L., Choi, K., & Kuhfeld, M. (2016). On the role of multilevel item response models in multisite evaluation studies for serious games. In H. F. O'Neil, E. L. Baker, & R. S. Perez (Eds.), *Using games and simulations for teaching and assessment: Key issues* (pp. 280–301). Routledge. https://doi.org/10.4324/9781315817767
- Center for Advanced Technology in Schools. (2012). CATS developed games (CRESST Resource Report No. 15). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Center for Advanced Technology in Schools. (2013a). *CATS knowledge and item specifications: Functions*. University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Center for Advanced Technology in Schools. (2013b). *CATS knowledge and item specifications: Rational number equivalence*. University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Center for Advanced Technology in Schools. (2013c). *CATS knowledge and item specifications: Solving equations*. University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Chi, M. T., Glaser, R., & Farr, M. J. (1988). The nature of expertise. Psychology Press.

- Choi, K., Parks, C. B., Feng, T., Redman, E. J. K. H., & Chung, G. K. W. K. (2021). Molly of Denali analytics validation study final report (Deliverable to PBS KIDS). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Choi, K., Suh, Y. S., Chung, G. K. W. K., Redman, E. J. K. H., Feng, T., & Parks, C. B. (2021). A secondary analysis of the Molly of Denali RCT data: Examining the relationship among game-based indicators, video usage, and external outcomes using advanced psychometric modeling and population data (Deliverable to EDC). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Chung, G. K. W. K. (2015). Guidelines for the design, implementation, and analysis of game telemetry. In C. S. Loh, Y. Sheng, & D. Ifenthaler (Eds.), Serious games analytics: Methodologies for performance measurement, assessment, and improvement (pp. 59–79). Springer.
- Chung, G. K. W. K., & Baker, E. L. (2003). An exploratory study to examine the feasibility of measuring problem-solving processes using a click-through interface. *Journal of Technology, Learning, and Assessment, 2*(2). http://ejournals.bc.edu/ojs/index.php/jtla/article/view/1662
- Chung, G. K. W. K., Baker, E. L., Vendlinski, T. P., Buschang, R. E., Delacruz, G. C., Michiuye, J. K., Wainess, R., & Bittick, S. J. (2010, April 30—May 4). Testing instructional design variations in a prototype math game. In R. Atkinson (Chair), Current perspectives from three national R&D centers focused on gamebased learning: Issues in learning, instruction, assessment, and game design [Structured poster session]. Annual meeting of the American Educational Research Association, Denver, CO, United States.
- Chung, G. K. W. K., Choi, K., Baker, E., & Cai, L. (2014). The effects of math video games on learning: A randomized evaluation study with innovative impact estimation techniques (CRESST Report 841). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Chung, G. K. W. K., de Vries, L. F., Cheak, A. M., Stevens, R. H., & Bewley, W. L. (2002). Cognitive process validation of an online problem solving assessment. *Computers in Human Behavior*, *18*, 669–684.

- Chung, G. K. W. K., Delacruz, G. C., de Vries, L. F., Kim, J.-O., Bewley, W. L., de Souza e Silva, A. A., Sylvester, R. M., & Baker, E. L. (2004). Determinants of rifle marksmanship performance: Predicting shooting performance with advanced distributed learning assessments (Deliverable to Office of Naval Research). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Chung, G. K. W. K., Delacruz, G. C., Dionne, G. B., Baker, E. L., Lee, J. J., & Osmundson, E. (2016). *Towards individualized instruction with technology-enabled tools and methods* (CRESST Report 854). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Chung, G. K. W. K., Delacruz, G. C., Dionne, G. B., & Bewley, W. L. (2003). Linking assessment and instruction using ontologies. *Proceedings of the I/ITSEC*, 25, 1811–1822.
- Chung, G. K. W. K., & Feng, T. (2024). From clicks to constructs: An examination of validity evidence of game-based indicators derived from theory. In M. Sahin & D. Ifenthaler (Eds.), Assessment analytics in education. Advances in analytics for learning and teaching (pp. 327–354). Springer. https://doi.org/10.1007/978-3-031-56365-2_17
- Chung, G. K. W. K., Madni, A., & Baker, E. L. (2015). *EAITS test and evaluation final report* (Deliverable to Raytheon BBN). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Chung, G. K. W. K., Madni, A., Iseli, M., Koenig, A., & Baker, E. L. (2014). *CRESST Assessment report: Validation of knowledge probe methodology* (Deliverable to Raytheon BBN). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Chung, G. K. W. K., Michiuye, J. K., Brill, D. G., Sinha, R., Saadat, F., de Vries, L. F., Delacruz, G. C., Bewley, W. L., & Baker, E. L. (2002). *CRESST human performance knowledge mapping system* (Final deliverable to the Office of Naval Research). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).

- Chung, G. K. W. K., Nagashima, S. O., Espinosa, P. D., Berka, C., & Baker, E. L. (2008). An exploratory investigation of the effect of individualized computer-based instruction on rifle marksmanship performance and skill (CRESST Tech. Rep. No. 754). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Chung, G. K. W. K., O'Neil, H. F., Delacruz, G. C., & Bewley, W. L. (2005). The role of affect on novices' rifle marksmanship performance. *Educational Assessment*, 10, 257–275.
- Chung, G. K. W. K., & Parks, C. (2015). Bundle 1 computational model—v1 (Measurement) (Deliverable to PBS KIDS). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Chung, G. K. W. K., Parks, C. B., Redman, E. J. K. H., Choi, K., Kim, J., Madni, A., & Baker, E. L. (2016). *PBS KIDS final report* (Deliverable to PBS KIDS). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Chung, G. K. W. K., Redman, E. H., & Madni, A. (2018, January 4–7). *Computer-based assessment of nonroutine problem solving* [Presentation]. Sixteenth Annual Hawaii International Conference on Education, Honolulu, HI, United States.
- Chung, G. K. W. K., & Roberts, J. (2018, April 13–17). Common learning analytics for learning games. In E. L. Baker (Chair), *Games and simulations: Learning analytics and metrics* [Symposium]. Annual meeting of the American Educational Research Association, New York, NY, United States.
- Chung, G. K. W. K., Ruan, Z., & Redman, E. J. K. H. (2021, April 9–12). A qualitative comparison of young children's performance on analogous digital and hands-on tasks: Assessment implications [Paper presentation]. Annual meeting of the American Educational Research Association, Virtual Conference, United States.
- De Boeck, P., & Wilson, M. (2004). Explanatory item response models: A generalized linear and nonlinear approach. Springer Science & Business Media.

- de la Torre, J., & Song, H. (2009). Simultaneous estimation of overall and domain abilities: A higher-order IRT model approach. *Applied Psychological Measurement*, 33(8), 620–639.
- Delacruz, G. C. (2011). Games as formative assessment environments: Examining the impact of explanations of scoring and incentives on math learning, game performance, and help seeking (CRESST Report 796). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- DiCerbo, K. E., Mislevy, R. J., & Behrens, J. T. (2016). Inference in game-based assessment. In H. F. O'Neil, E. L. Baker, & R. S. Perez (Eds.), *Using games and simulations for teaching and assessment: Key issues* (pp. 253–279). Routledge. https://doi.org/10.4324/9781315817767
- Education Development Center, Inc., & SRI International. (2021). *Mahsi'choo for the Info! Molly of Denali teaches children about informational text*. https://www.edc.org/sites/default/files/uploads/EDC-SRI-Mahsi-choo-Info-Summary.pdf
- Ericsson, K. A., & Charness, N. (1994). Expert performance: Its structure and acquisition. *American Psychologist*, 49(8), 725–747.
- Espinosa, P. D., Nagashima, S. O., Chung, G. K. W. K., Parks, D., & Baker, E. L. (2009). Development of sensor-based measures of rifle marksmanship skill and performance (CRESST Tech. Rep. No. 756). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Feng, T. (2019, April 5–9). Using game-based measures to assess children's scientific thinking about force [Poster presentation]. Annual meeting of the American Educational Research Association, Toronto, Canada.
- Feng, T., & Cai, L. (2024). Sensemaking of process data from evaluation studies of educational games: An application of cross-classified item response theory modeling. *Journal of Educational Measurement*. https://doi.org/10.1111/jedm.12396

- Feng, T., & Cai, L. (2025). Integrating data from multiple sources in evaluation studies of educational games: An application of cross-classified item response theory modeling. In J. L. Plass & X. Ochoa (Eds.), *Serious games* (Vol. 15259, pp. 70–76). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-74138-8_6
- Feng, T., & Chung, G. K. W. K. (2022, April 22–25). Extracting debugging indicators based on distance to solution in a block-based programming game. In G. K. W. K. Chung (Chair), *Game-based indicators of learning processes: Extraction methods, validity evidence, and applications* [Symposium]. Annual meeting of the American Educational Research Association, San Diego, CA, United States.
- Feng, T., Chung, G. K. W. K., Choi, K., & Redman, E. J. K. H. (2025). *EDC SRI Wombats secondary analysis—Final report* (Deliverable to PBS KIDS). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Fitts, P. M., & Posner, M. I. (1967). Human performance. Brooks/Cole.
- Gates, A. I. (1918). The abilities of an expert marksman tested in the psychological laboratory. *Journal of Applied Psychology*, *2*, 1–14.
- Gentner, D., & Gentner, D. R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner, & A. L. Stevens (Eds.), *Mental models* (pp. 99–129). Psychology Press.
- Gómez, M. J., Ruipérez-Valiente, J. A., & Clemente, F. J. G. (2022). A systematic literature review of game-based assessment studies: Trends and challenges. IEEE Transactions on Learning Technologies, 1–16. https://doi.org/10.1109/TLT.2022.3226661
- Gorman, T. P., Purves, A. C., & Degenhart, R. E. (1988). The IEA study of written composition I: The international writing tasks and scoring scales. Pergamon.
- Graves, D. (1978). Balance the basics: Let them write. Ford Foundation.
- Gris, G., & Bengtson, C. (2021). Assessment measures in game-based learning research: A systematic review. *International Journal of Serious Games*, 8(1), Article 1. https://doi.org/10.17083/ijsg.v8i1.383

- Gruber, T. R. (1995). Toward principles for the design of ontologies used for knowledge sharing? *International Journal of Human-Computer Studies*, 43(5), 907–928. https://doi.org/10.1006/ijhc.1995.1081
- Haladyna, T. M., & Rodriguez, M. C. (2013). *Developing and validating test items* (1st ed.). Routledge. https://doi.org/10.4324/9780203850381
- Herl, H. E., Baker, E. L., & Niemi, D. (1996). Construct validation of an approach to modeling cognitive structure of US history knowledge. *Journal of Educational Research*, 89(4), 206–218.
- Herl, H. E., O'Neil Jr, H. F., Chung, G. K., & Schacter, J. (1999). Reliability and validity of a computer-based knowledge mapping system to measure content understanding. *Computers in Human Behavior*, *15*(3–4), 315–333.
- Ihlenfeldt, S., Chung, G. K. W., K., Lyons, S., Lawson, J., & Redman, E. J. K. H. (2025). Modeling the relationships among online Solitaire gameplay and measures of cognition (CRESST Report 877). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Iseli, M. R., & Jha, R. (2016). Computational issues in modeling user behavior in serious games. In H. F. O'Neil, E. L. Baker, & R. S. Perez (Eds.), *Using games and simulations for teaching and assessment: Key issues* (pp. 21–40). Routledge.
- Iseli, M. R., Koenig, A. D., Lee, J. J., & Wainess, R. (2010). Automated assessment of complex task performance in games and simulations (CRESST Report 775). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Iseli, M. R., Lee, J. J., Schenke, K., Leon, S., Lim, D., Jones, B., & Cai, L. (2019). Simulation-based assessment of ultrasound proficiency (CRESST Report 865). UCLA/CRESST
- Jiao, H., He, Q., & Veldkamp, B. P. (2021). Editorial: Process data in educational and psychological measurement. *Frontiers in Psychology*, 12. https://www.frontiersin.org/articles/10.3389/fpsyg.2021.793399
- Kerr, D. (2014). Identifying common mathematical misconceptions from actions in educational video games (CRESST Report 838). UCLA/CRESST

- Kerr, D., & Chung, G. K. W. K. (2012a). Identifying key features of student performance in educational video games and simulations through cluster analysis. *Journal of Educational Data Mining*, *4*, 144–182.
- Kerr, D., & Chung, G. K. W. K. (2012b). Using cluster analysis to extend usability testing to instructional content (CRESST Report 816). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Kerr, D., & Chung, G. K. W. K. (2013a). Identifying learning trajectories in an educational video game. In R. Almond & O. Mengshoel (Eds.), *Proceedings of the 2013 UAI Application Workshops: Big Data Meet Complex Models and Models for Spatial, Temporal and Network Data* (pp. 20–28). http://ceur-ws.org/Vol-1024/
- Kerr, D., & Chung, G. K. W. K. (2013b). The effect of in-game errors on learning outcomes (CRESST Report 835). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Kim, Y. J., & Ifenthaler, D. (2019). Game-based assessment: The past ten years and moving forward. In D. Ifenthaler & Y. J. Kim (Eds.), *Game-based assessment revisited: Advances in game-based learning* (pp. 3–11). Springer. https://doi.org/10.1007/978-3-030-15569-8_1
- Koenig, A. D., Lee, J. J., Iseli, M., & Wainess, R. (2010). A conceptual framework for assessing performance in games and simulation (CRESST Report 771). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Kumar, R., Chung, G. K. W. K., Madni, A., & Roberts, B. (2015). First evaluation of the physics instantiation of a problem-solving based online learning platform. In C. Conati, N. Hefferman, A. Mitrovic, & M. F. Verdejo (Eds.), Lecture Notes in Computer Science: Vol. 9112. Artificial Intelligence in Education (pp. 686–689). Springer.
- Landers, R. (2015). Special issue on assessing human capabilities in video games and simulations. *International Journal of Gaming and Computer-Mediated Simulations*, 7(4), iv–viii.

- Levy, R. (2019). Dynamic Bayesian network modeling of game-based diagnostic assessments. *Multivariate Behavioral Research*, *54*(6), 771–794. https://doi.org/10.1080/00273171.2019.1590794
- Lindner, M. A., & Greiff, S. (2023). Process data in computer-based assessment. *European Journal of Psychological Assessment*, 39(4), 241–251. https://doi.org/10.1027/1015-5759/a000790
- Madni, A., Griffin, N., & Yang, J. S. (2013, April 27—May 1). Integrating assessment of SEL into an early childhood science learning context [Paper presentation]. Annual meeting of the American Educational Research Association, San Francisco, CA, United States
- Mislevy, R. J., Corrigan, S., Oranje, A., DiCerbo, K., Bauer, M. I., von Davier, A., & John, M. (2015). Psychometrics and game-based assessment. In F. Drasgow (Ed.), *Technology and testing* (pp. 23–48). Routledge. https://doi.org/10.4324/9781315871493
- Nagashima, S. O., Chung, G. K. W. K., Espinosa, P. D., & Berka, C. (2009). Sensor-based assessment of basic rifle marksmanship. *Proceedings of the I/ITSEC*, Orlando, FL.
- Niemi, D., & Baker, E. L. (1998, January). Design and development of a comprehensive assessment system: Pilot testing, scoring, and refinement of mathematics and language arts performance assessments (Final Deliverable). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- O'Neil, H. F. Jr, & Baker, E. L. (1987). Issues in intelligent computer-assisted instruction, evaluation and measurement. In T. B. Gutkin & S. L. Wise (Eds.), The computer and decision-making process (pp. 199–224). Erlbaum.
- O'Neil, H. F., Baker, E. L., & Linn, R. L. (1990, April 16–20). *Performance assessment framework* [Paper presentation]. Annual meeting of the American Educational Research Association, Boston, MA, United States.

- O'Neil, H. F., Baker, E. L., Ni, Y., Jacoby, A., & Swigger, K. M. (1994). *Human benchmarking for the evaluation of expert systems*. In H. F. O'Neil, Jr., & E. L. Baker (Eds.), Technology assessment in software applications (pp. 13–45). Lawrence Fribaum Associates
- O'Neil, H. F., Mayer, R. E., Rueda, R., & Baker, E. L. (2021). Measuring and increasing self-efficacy in a game. In H. F. O'Neil, E. L. Baker, R. S. Perez, & S. E. Watson (Eds.), Using cognitive and affective metrics in educational simulations and games: Applications in school and workplace contexts (pp. 131–158). Routledge/ Taylor & Francis.
- Oranje, A., Mislevy, B., Bauer, M. I., & Jackson, G. T. (2019). Summative game-based assessment. In D. Ifenthaler & Y. J. Kim (Eds.), *Game-based assessment revisited* (pp. 37–65). Springer. https://doi.org/10.1007/978-3-030-15569-8_3
- Organisation for Economic Co-operation and Development (OECD). (2014). PISA 2012 Results: Creative problem solving: Students' skills in tackling real-life problems (Volume V). OECD Publishing. http://dx.doi.org/10.1787/9789264208070-en
- Organisation for Economic Co-operation and Development (OECD). (2021). *OECD digital education outlook 2021: Pushing the frontiers with artificial intelligence, blockchain and robots.* https://doi.org/10.1787/589b283f-en
- Quellmalz, E. S. (1982). *Designing writing assessments: Balancing fairness, utility, and cost* (CSE Report 188). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Rasch, G. (1960). *Probabilistic models for some intelligence and attainment tests* (Expanded ed.). University of Chicago Press.
- Redman, E. J. K. H., Chung, G. K. W. K., Feng, T., Parks, C. B., Schenke, K., Michiuye, J. K., Choi, K., Ziyue, R., & Wu, Z. (2020). *Cat in the Hat Builds That analytics validation study—final deliverable* (Deliverable to PBS KIDS). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).

- Redman, E. J. K. H., Chung, G. K. W. K., Schenke, K., Maierhofer, T., Parks, C. B., Chang, S. M., Feng, T., Riveroll, C. S., & Michiuye, J. K. (2018). Connected learning final report (Deliverable to PBS KIDS). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Redman, E. J. K. H., Feng, T., Parks, C. B., Choi, K., & Chung, G. K. W. K. (2023). Learning-related analytics KPI—KPI final report (Deliverable to PBS KIDS). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Redman, E. J. K. H., Feng, T., Parks, C. B., Chung, G. K. W. K., Choi, K., & Cai, L. (2025). Wombats analytics evaluation —Final report (Deliverable to PBS KIDS). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Redman, E. J. K. H., Parks, C. B., Michiuye, J. K., Suh, Y. S., Chung, G. K. W. K., Kim, J., & Griffin, N. (2021). Social-emotional learning games validity study (exploratory study): Final study report. University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Richardson, M. W., Russell, J. T., Stalnaker, J. M., & Thurstone, L. L. (1933). *Manual of examination methods*. The University of Chicago. http://hdl.handle.net/2027/uiug.30112066775344
- Roberts, J. D., Chung, G. K. W. K., & Parks, C. B. (2016). Supporting children's progress through the PBS KIDS learning analytics platform. *Journal of Children and Media*, 10, 257–266.
- Roberts, J. D., Younger, J. W., Corrado, K., Felline, C., & Lovato, S. (in press). Practical examples of assessment in the service of learning at PBS KIDS. In Tucker, E., Everson, E., Baker, E. L., & E. W. Gordon (Eds.), Handbook for assessment in the service of learning, Volume III, Examples of assessment in the service of learning. University of Massachussets Amherst.
- Ruiz-Primo, M. A., Shavelson, R. J., Li, M., & Schultz, S. E. (2001). On the validity of cognitive interpretations of scores from alternative concept-mapping techniques. *Educational Assessment*, 7(2), 99–141.

- Rupp, A. A., Templin J., & Henson R. (2010). *Diagnostic measurement: Theory, methods, and applications*. Guilford Press.
- Savitsky, E. (2013). U.S. Patent No. 8,480,404. U.S. Patent and Trademark Office.
- Scardamalia, M., Bereiter, C., & Steinbach, R. (1984). Teachability of reflective processes in written composition. *Cognitive Science*, 8(2), 173–190.
- Schacter, J., Herl, H. E., Chung, G. K. W. K., Dennis, R. A., & O'Neil, H. F. (1999). Computer-based performance assessments: A solution to the narrow measurement and reporting of problem-solving. *Computers in Human Behavior*, 15, 403–418.
- Shute, V., & Wang, L. (2016). Assessing and supporting hard-to-measure constructs in video games. In A. A. Rupp & J. P. Leighton (Eds.), *The handbook of cognition and assessment* (pp. 535–562). John Wiley & Sons. https://doi.org/10.1002/9781118956588.ch22
- Sireci, S. G. (2016). Commentary on chapters 1–4: Using technology to enhance assessments. In F. Drasgow (Ed.), *Technology and testing: Improving educational and psychological measurement* (pp. 104–108). Routledge. https://doi.org/10.4324/9781315871493
- Stevens, R., Ikeda, J., Casillas, A., Palacio-Cayetano, J., & Clyman, S. (1999). Artificial neural network-based performance assessments. *Computers in Human Behavior*, 15(3), 295–313. https://doi.org/10.1016/S0747-5632(99)00025-4
- Tadayon, M., & Pottie, G. J. (2020). Predicting student performance in an educational game using a hidden Markov model. *IEEE Transactions on Education*, 63(4), 299–304.
- Tlili, A., Chang, M., Moon, J., Liu, Z., Burgos, D., Chen, N.-S., & Kinshuk. (2021).

 A systematic literature review of empirical studies on learning analytics in educational games. *International Journal of Interactive Multimedia and Artificial Intelligence*, 7(2), 250–261. http://doi.org/10.9781/ijimai.2021.03.003

- U.S. Department of Education, Institute of Education Sciences, What Works Clearinghouse. (2015, November). WWC review of the report: The effects of math video games on learning: A randomized evaluation study with innovative impact estimation techniques. http://whatworks.ed.gov
- U.S. Marine Corps. (2001). Rifle marksmanship (PCN 144 000091 00, MCRP 3-01A).
- VanLehn, K., Chung, G., Grover, S., Madni, A., & Wetzel, J. (2016). Learning science by constructing models: Can Dragoon increase learning without increasing the time required? *International Journal of Artificial Intelligence in Education*, 26, 1033-1068. https://doi.org/10.1007/s40593-015-0093-5
- Vendlinski, T. P., Chung, G. K. W. K., Binning, K. R., & Buschang, R. E. (2011). *Teaching rational number addition using video games: The effects of instructional variation.* (CRESST Report 808). University of California, Los Angeles, National Center for Research on Evaluation, Standards, and Student Testing (CRESST).
- Wigger, K. M., O'Neil, H. F., Jr., & Ni, Y. (1990). Evaluation of expert systems: A review of the literature. Los Angeles: University of California, Center for the Study of Evaluation/Center for Technology Assessment. https://apps.dtic.mil/sti/tr/pdf/ADA233601.pdf
- Wiley, K., Robinson, R., & Mandryk, R. L. (2021). The making and evaluation of digital games used for the assessment of attention: Systematic review. *JMIR Serious Games*, 9(3), e26449. https://doi.org/10.2196/26449
- Zumbo, B. D., Maddox, B., & Care, N. M. (2023). Process and product in computer-based assessments: Clearing the ground for a holistic validity framework. *European Journal of Psychological Assessment*, 39(4), 252–262. https://doi.org/10.1027/1015–5759/a00074.