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Designing and Evaluating Virtual Reality Applications for a Machine Design Course

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Dr. Gregg's career sits at the unique intersection of instructional design, faculty development, educational technology leadership, curriculum planning, and educational research and evaluation. She is an established higher education professional with over twenty years' experience in online, distance education. As the manager of an instructional design (ID) team responsible for the design, development, and support of nearly 150 courses, she worked with a diverse portfolio including STEM, Education, Law, and Liberal Arts disciplines. Faculty development has been a key responsibility throughout her career, having developed and taught faculty workshops across disciplines in online pedagogy and instructional technologies. She has teaching experience in online and residential contexts and was an adjunct instructor for the Learning, Design, and Technology masters' program and taught for four years in the Communication Arts and Sciences department where course formats included large (180+) lectures, computer labs, and public speaking classes. She has led complex projects requiring collaboration among faculty and staff from across departments and campuses, including leadership for Penn State World Campus of the university-wide learning management system pilots. She previously co-led the University's eEducation council comprised of instructional design leaders across the university and served on the provost's online educational resources (OER) committee. In her current position as the Director of Online Pedagogy and an Assistant Teaching Professor in Penn State's Mechanical Engineering department, she facilitates faculty development to maximize teaching and learning efficacy throughout the ME curriculum, with a primary focus on online learning. She is also responsible for leading quality instructional design for residential and online offerings; facilitating an activity community of practice for Mechanical Engineering faculty dedicated to continuous quality improvement in pedagogy; and leading and evaluating emerging educational technology innovations such as digital badges, adaptive learning, and learning analytics. She conducts research related to the scholarship of teaching and learning in Mechanical Engineering to improve practice in the department and contribute to the national and international Engineering Education research community through presentations and publications.

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Introduction

Machine design is an iterative decision-making process that requires students to select and assemble machine elements to create a device that performs a desired task. A machine designer must possess knowledge of basic physical sciences and familiarity with machine components such as shafts, pulleys, and bearings; creativity also plays a very important role. Machine (or Mechanical) Design is a required course in most undergraduate mechanical engineering programs to help students gain these complex skills. The large size of Machine Design courses and fixed classroom spaces make it logistically challenging to provide hands-on experiences for all students. It is commonplace, therefore, to teach machine design without physical machines, instead relying on images, 2D videos, and computer-assisted design (CAD) models to demonstrate the functionality of different components. While having students work in CAD is an important step in deepening their abilities with machine design, it puts students who lack familiarity with machine components at a disadvantage. Additionally, an important requirement for a successful design is to have a sense of dimension and how elements of different sizes can potentially work together. Without experiences where students can perceive actual sizes, it can be difficult to develop a sense of dimensional scale which can lead to misconceptions and the development of unrealistic designs.

Innovative technologies such as virtual reality (VR) offer potential solutions to the persistent challenge of learning about machine design without physically interacting with the machine components. A VR system can also provide information and insight beyond what a physical model allows. VR can enlarge small scale items or slow down fast mechanisms to allow the user to interact better and understand the device. At the same time, these technologies can vary significantly in terms of realism, time to create, learner experience, and impact on learning. It is especially important in working with these technologies that learning experience is prioritized and studied.

In this paper, we delineate the pedagogical requisites and learning objectives of a Machine Design course. We focus on the potentialities and constraints of current educational methodologies that employ images, CAD programs, and 2D video and look at the use of VR within engineering education. We then present the evaluation of the integration of a Virtual Reality (VR) application on student learning and confidence outcomes during the Fall 2023 offering of a Machine Design course. We utilized a pre-post design comparing the impact of VR combined with Traditional Instructional Method (VRTIM) with the impact of Traditional Instructional Method (TIM) only.

Literature Review

Machine Design Curriculum

A machine design course in mechanical engineering primarily focuses on analyzing the performance and potential failure of machine components. It is a required course in the mechanical engineering (ME) curriculum, acting as a vital link between theoretical physics concepts and their practical application in real-world engineering challenges. This course allows students to synthesize knowledge acquired in earlier courses (statics, dynamics, and mechanics of materials) and apply it to design functional machines and devices [1]. The ability to design machines is a fundamental skill applicable across various engineering domains, making it a crucial aspect of the curriculum.

Machine design is an iterative decision-making process, demanding students to select and assemble machine elements to create devices that fulfill specific tasks [2]. It encompasses not only applied science and engineering but also an art where aesthetic sense plays a significant role [3]. Designing a suitable mechanism requires considerable imagination for any given purpose.

The content of a machine design course can be divided into two main parts. The initial section covers general concepts of mechanical failure, covering aspects like failure under static loads, fatigue, and surface failure due to contact between metal elements such as surface wear. These concepts are universally applicable to any machine element. The latter part of the course focuses on applying these concepts to analyze specific machine elements such as gears, bearings, shafts, and others. The objective is to determine the safety factor for specified performance parameters and predict the expected life of the machine element.

ABET, the Accreditation Board for Engineering and Technology, establishes standards for engineering programs, emphasizing the need for students to design within various constraints, including economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability [4]. Meeting these broad ABET requirements is achievable through various instructional approaches and course designs.

Teaching machine design traditionally is challenging as many students lack familiarity with machine components and their real-world applications [4]. Due to logistical challenges, such as large class sizes and limited access to physical devices, instructors often resort to using images, videos, and CAD models to illustrate machine component functionality. Lectures typically involve board explanations or pre-designed slides, which may lack interactivity. Although interactive tools like Top Hat [5] that allow students to ask and answer questions in real-time can be incorporated for active learning, the absence of physical machines makes it difficult for students to grasp the interactions between different machine elements and their effects on the design process [6]. One possible solution to this challenge is the use of virtual reality to allow for scalable hands-on learning experiences.

Virtual Reality and Engineering Education

While augmented reality enhances the real world with simulated components overlayed on the physical world, virtual reality refers to a more immersive simulated world which replaces the real, physical world. There have been many applications of virtual reality in the last 20 years within engineering education [7]. Current recent suggests that there are three primary benefits of using VR in a course: improved communication, motivation, and cognition. VR can be an effective way to communicate complex concepts [7]. Many engineering applications involve moving objects or systems, such as a vibrating mass-spring-damper system or a gear train. These moving systems are not easily described in a drawn figure. VR allows for the motion to be seen, or experienced, by the student. This, in turn, allows the student to internalize the concepts. VR can also be used for applications that are not safe, such as crane operations [9].

The novelty of using VR can also motivate and hold the student's attention. At the same time, it has been observed that several VR sessions or activities are needed before students are comfortable with the technology and can then focus fully on the lesson content [10]. VR simulations can also be constructed into a game to add a competitive component to the learning process [11]. This gaming application had students working in teams to build and test gear trains, including planetary gears. Pre- and post-testing showed that the VR gaming simulation improved students conceptual test score average from 59% to 83%.

There are also cognitive improvements from using VR as a person learns through sensory experiences (embodied cognition) [12]. The surrounding world can be used to organize concepts and thoughts, such as taking notes, drawing figures, or manipulating objects (real or virtual). There are benefits to a multimodal learning environment that includes verbal (words) and visual (figures) forms of communication. In defining modes, the term “verbal” includes words spoken and written. Presenting information in multimode allows a person to absorb more information than when only one mode, say only written descriptions, is used. Each mode of communication can become saturated but additional information can be absorbed using a second mode. It is important, however, that information is presented in the two modes at the same time or coordinated. A verbal description presented before the visual cues can cause cognitive overload due to information needing to be remembered and then recalled when the visual material is presented [13].

While all simulations provide the benefits of improved communication, motivation, and cognition, studies have shown an additional benefit from using immersive VR, such as a head mounted display [13], [10], [15]. Several features of immersive VR have been found to enhance student learning. It was found that the physical level of immersion was important. Seeing only the virtual world and not the real world allowed the student to focus completely on the simulation and experience the objectives of the session. The benefits of the immersive environment were found even when the resolution or realism of the VR was limited. When the real world could not be seen, the student was fully absorbed in the simulated experience. Pointing with motion sensing gloves, remotes, or eye detection gave a more realistic experience than using a mouse and keyboard commands. Imagination or belief that the user is in the virtual environment is impacted by immersion and interactivity of the virtual experience. VR laboratories, testing, and demonstrations can provide students with a better intuitive understanding of the content.

Study Context

Machine Design at Penn State

Over the past eight years, Dr. Daniel Cortes (an author on this paper) has been the instructor for six sections of a machine design course, which has been offered in-person through traditional instruction. The instructional approach primarily involves lectures, where Cortes writes on a tablet which is then projected onto multiple room screens. Theoretical concepts, mathematical procedures, and examples are conveyed using this methodology, supplemented with elements of active learning facilitated by Top Hat. This includes student participation in calculations akin to those in provided examples and discussion-stimulating questions. However, the experience has brought forth various challenges within the context of the mechanical engineering program at the Pennsylvania State University (Penn State).

The department of mechanical engineering at Penn State receives an annual influx of 300 to 400 junior students who have declared mechanical engineering as their major. Given that machine design is a mandatory course, two sessions per semester, each accommodating around 100 students, are offered. The considerable class size presents both challenges and limited opportunities for hands-on learning experiences. Primary among these challenges is the grading workload, mainly comprising weekly homework assignments and exams. The size of the class often dissuades instructors from implementing open-ended design projects. While it's feasible to bring small-scale props, models, or actual machine elements to class, students have limited time for interaction or exploration. Consequently, videos and images are employed to illustrate the functionality and interactions between machine elements. The volume of students also presents some opportunities. A class contribution assignment is typically incorporated where students are asked to solve a problem from the textbook and record a video explaining the solution. With consent from the students, the videos are then made available to other students who can use them as study material for exams or as just additional information. Given the class size, many videos covering all the topics in the course can be obtained.

Despite being uncommon in the department, Cortes integrates a project into the course. This project involves the design of a gearbox, undertaken in groups of two or three students, with varying design specifications between teams. The open-ended nature of the project allows students to select parameters for gears, bearings, and shafts, provided the safety factors fall within specified ranges. While this approach mirrors real-world design processes, it introduces challenges, such as the potential selection of unrealistic parameters, including oversized components or aesthetically unacceptable devices. Another recurrent challenge arises from questions about the connections between elements, such as gears or bearings to shafts. Cortes identifies a lack of familiarity with these machine elements as a key factor contributing to this challenge. These difficulties make incorporating real-world design exercises particularly demanding for faculty and teaching assistants. There are also equity implications as culturally males are generally encouraged to interact with machine elements more early in their lives than females and this can leave some female students feeling "behind" in the curriculum [16].

Shifting Gears: Machine Design VR Application

To address these challenges and provide students more opportunities for hands-on learning experiences, a VR game—*Shifting Gears*—was developed specifically for the Machine Design class and implemented during the fall 2023 semester as a required learning activity. In the *Shifting Gears* application, the player interacts with and manipulates the specific machine elements of gears, bearings, and shafts in the context of a gearbox. Players are completely immersed in the game and wear a headset and use hand controls to navigate the multi-room space. To see the images from *Shifting Gears* application described below, please see the corresponding figures in the Appendix. To access a complete video walkthrough of the game, go to https://bit.ly/machineelements. Also note that in a future paper, we will discuss the process for designing and developing the game but here will focus on its major features.

In Level 0, students initially select the game and then enter an open hallway (Figs. A.1 and A.2). They are then directed to Level 1. This first level is designed to familiarize learners with the key machine elements through hands-on sorting experiences. Once they enter the Level 1 room, they see a table with several machine elements on it (Fig. A.3). Students are then instructed to select one of the element types (i.e., gears, shafts, bearings) which then highlights several variations in size and composition of the selected element type. A poster is also displayed directly above the table with more information about the element. Students can pick up the elements to inspect them before sorting them into their specific type (Fig. A.4). Students are then required to sort each element into its appropriate virtual bin correctly. When the object is placed correctly, it turns green (Fig. A.5). After sorting the variations of each element, students then work with over-sized versions of the elements, allowing them to focus on finer technical details (Fig. A.6).

On completing Level 1, students navigate to the next level, Level 2 (Fig. A.7), where they progress from the knowledge level of Bloom's taxonomy to the application level [17]. Students are first directed to an activity related to rotational direction and then one related to calculating rotational speed (Figs. A.8 and A.9). In the last activity of Level 2, students assemble a gearbox (Fig. A.10). After successfully assembling the gearbox, students can animate it before ending the VR application.

Methods

The VR game *Shifting Gears* was implemented in a Fall 2023 semester section of the Machine Design course and a quantitative study design was used [18], [19] to investigate the following evaluation questions.

Q1: Does the use of VR technology in a machine design course impact engineering students' perceptions of fun and confidence with VR?

Q2: Was VR combined with traditional instructional methods (VRTIM) more effective in increasing knowledge of specific machine elements when compared to traditional instructional methods (TIM) alone?

Q3: Was VR combined with traditional instructional methods (VRTIM) more effective in increasing confidence pertaining to specific machine elements than traditional instructional methods (TIM) alone?

Study Design

The VR intervention, *Shifting Gears,* was offered as a required course assignment and students were informed of the game assignment in the syllabus and course lecture. Students were also provided with video tutorials in the course learning management system before playing that showed them how to correctly put on the headset, how to use the hand controls, and how to navigate within the game. To access the game, they went to a lab on campus that had headsets with *Shifting Gears* loaded. The lab attendant recorded who completed the game and informed Professor Cortes.

While *Shifting Gears* focused only on gears, shafts, and bearings, several other machine elements including screws, springs, and clutches were also taught in the course throughout the semester. The study was designed, therefore, to consider how the use of VR in addition to traditional instructional methods (VRTIM) for the teaching of gears, bearings, and shafts compared to the use of traditional instructional methods (TIM) only for screws, springs, and clutches.

Rather than experimental and control groups of students with some receiving the treatment and others not, all students experienced the same learning activities throughout the course. This meant that they all learned about gears, shafts, and bearings through a combination of their participation in the VR game, *Shifting Gears,* and traditional instructional methods such as lectures and readings (VRTIM). They then learned about screws, springs, and clutches through traditional instructional methods (TIM) only.

There were three surveys assigned during the course. The first survey—PRE-INTERVENTION SURVEY—captured baseline data pertaining to knowledge and confidence with the six machine elements (gears, shafts, bearings, screws, springs, clutches) as well as students' approaches to new technologies and attitudes toward VR generally (pertaining to perceptions of both fun and confidence). The first survey was distributed before students had been exposed to any of the six machine elements.

The second survey—POST-INTERVENTION SURVEY 1—was distributed after students had played the *Shifting Gears* VR game and had learned about gears, shafts, and bearings through traditional instructional methods. This second survey asked the same knowledge and confidence questions pertaining to gears, shafts, and bearings as were asked in the initial baseline survey.

The third survey—POST-INTERVENTION SURVEY 2—was distributed after students had learned about screws, springs, and clutches through traditional instructional methods only. This third survey asked the same knowledge and confidence questions pertaining to screws, springs, and clutches as were asked in the initial baseline survey. The third survey also repeated the baseline questions pertaining to students' perceptions of fun and confidence with VR. To see the semester timeline of when the surveys and instructional interventions took place, see Fig. 1. To see a graphical depiction of how the VR and traditional Instructional methods (VRTIM) were compared to traditional instructional methods (TIM) only, see Fig. 2.

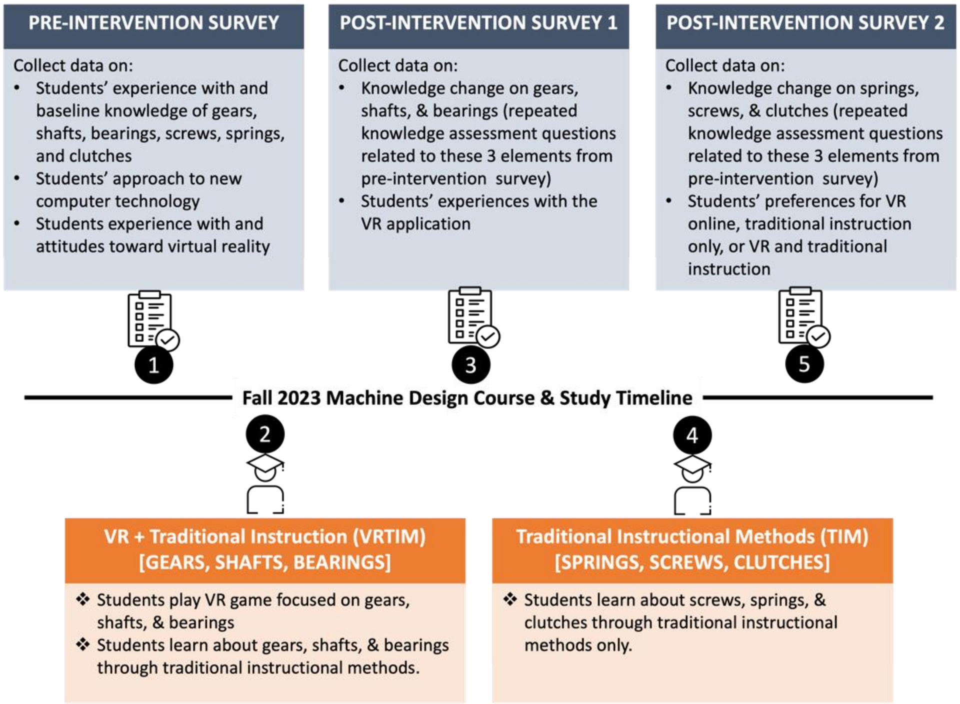

Fig. 1. Semester Timeline.

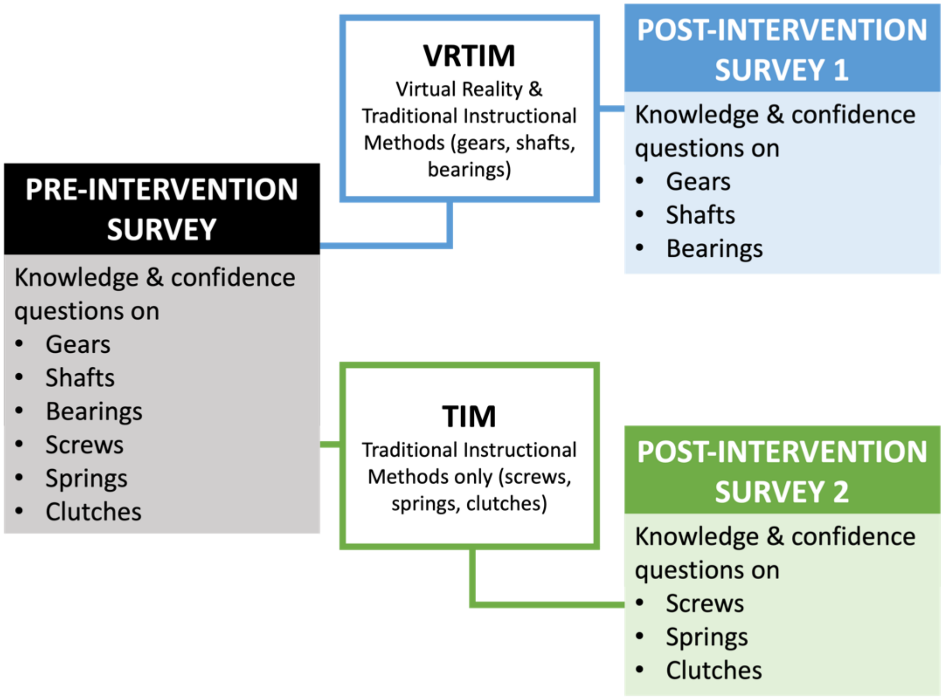

Fig. 2. Comparing VRTIM to TIM.

Results

The study evaluated the effectiveness of VR in a machine design course from multiple perspectives. It addresses whether VR impacts students' perceptions of fun and confidence (Q1), the comparative effectiveness of VR combined with traditional instructional methods (VRTIM) in enhancing knowledge of machine elements (Q2), and the influence of VR on students' confidence concerning specific machine elements (Q3). To address research questions Q1, Q2, and Q3, student survey data were analyzed using descriptive and inferential statistics.

Q1. Does the use of VR technology in a machine design course impact engineering students' perceptions of fun and confidence with VR?

Table 1 shows participants' reports on various aspects of their VR experience both before and after an intervention, measured on a 0-10 scale. The average rating for participants' willingness to interact with new technology (Pre-Interaction) was 7.14, which suggests a generally positive inclination towards new technology, with moderate variability (SD = 2.302). Prior experience with VR (Pre-Experience) was lower, with an average of 4.52, indicating less familiarity with VR among participants (SD = 2.783). Perceptions of fun with VR (Pre-Fun) was high before the intervention (M = 7.86, SD = 2.253) and increased after the intervention (Post-Fun M = 8.41, SD = 2.129), showing that participants perceived VR to be fun and their perception of that fun increased post-intervention. Confidence with VR also increased following the intervention, rising from a mean of 5.63 (SD = 2.831) to 7.44 (SD = 2.494), suggesting that the intervention had a positive effect on participants' confidence in using VR. Overall, the data suggest that participants were positively inclined towards VR technology and that the intervention improved their enjoyment and confidence with VR.

Table 1.
Descriptive statistics for VR perception on a 0-10 scale

Measure	N	Missing	Mean	Median	Mode	SD
Pre-Interaction	64	0	7.14	7.00	10	2.302
Pre-Experience	64	0	4.52	5.00	2	2.783
Pre-Fun	64	0	7.86	8.00	10	2.253
Post-Fun	64	0	8.41	9.00	10	2.129
Pre-Confidence	64	0	5.63	5.50	5	2.831
Post-Confidence	64	0	7.44	8.00	8	2.494

NOTE. Pre-Interaction = "In general, how do you like to interact with new computer technology? (Pre)"; Pre-Experience = "What is your prior experience with VR? (Pre)"; Pre-Fun = "How fun do you think VR is/can be? (Pre)"; Pre-Confidence = "How confident are you with VR? (Pre)". Post-Fun = "How fun do you think VR is/can be? (Post)"; Post-Confidence = "How confident are you with VR? (Post)"

A paired samples t-test was conducted to evaluate the impact of the intervention on participants' perceptions of fun and confidence with VR (Table 2). The test revealed a statistically significant increase in the perception of fun associated with VR, with a mean increase of 0.589 (95% CI [0.176, 1.002]), t(63) = 2.188, p = .006. The effect size for this increase, measured by Cohen's d, was 0.270, indicating a small to medium effect. Similarly, participants' confidence with VR showed a statistically significant improvement after the intervention, with a mean increase of 1.812 (95% CI [1.150, 2.475]), t(63) = 5.463, p < .001. The effect size for confidence, with a Cohen's d of 0.675, was medium to large, suggesting that the intervention had a more substantial impact on participants' confidence in using VR compared to their perception of fun. These results indicate that the intervention was effective in enhancing both the enjoyment and confidence levels of participants with VR, with a more pronounced effect on confidence.

Table 2.
Paired Samples t-Test and Effect Sizes for VR Perceptions

Measure	Mean Difference	SD Difference	SEM	95% CI Lower	95% CI Upper	T	df	p (two-tailed)	Cohen's d
Fun with VR	0.589	1.971	.208	0.176	1.002	2.188	63	.006	0.270
Confidence with VR	1.812	2.654	.332	1.150	2.475	5.463	63	< .001	0.675

*p < .05. **p < .01. ***p < .001. N = 64 for all analyses.

To examine the relationships among survey items pertaining to technology interaction preferences, experience of VR prior to the class, and pre and post measures of fun and confidence with VR, Kendall's Tau-b correlation analyses were conducted both before (Pre) and after (Post) an intervention (Table 3). The results indicated several significant correlations. Participants' general inclination to interact with new technology (Pre-Interaction) showed moderate positive correlations with their prior experience with VR (Pre-Experience, $\tau = .300$, $p < .01$), perceived fun of VR (Pre-Fun, $\tau = .240$, $p < .05$), and confidence with VR both before (Pre-Confidence, $\tau = .269$, $p < .01$) and after the intervention (Post-Confidence, $\tau = .304$, $p < .01$). This suggests that those who are more inclined to interact with new technology tend to have more experience with VR, find it more enjoyable, and feel more confident using it.

Prior experience with VR (Pre-Experience) was strongly correlated with the perceived fun of VR before the intervention (Pre-Fun, $\tau = .462$, $p < .001$) and participants' confidence in their ability to use VR both before (Pre-Confidence, $\tau = .655$, $p < .001$) and after the intervention (Post-Confidence, $\tau = .326$, $p < .001$). This pattern indicates that more experience with VR is associated with higher enjoyment and confidence levels. Interestingly, the fun aspect of VR (Pre-Fun) showed strong correlations with confidence levels before (Pre-Confidence, $\tau = .569$, $p < .001$) and after (Post-Confidence, $\tau = .426$, $p < .001$) the intervention, as well as with the post-intervention fun rating (Post-Fun, $\tau = .536$, $p < .001$). This suggests that enjoyment of VR is closely linked to users' confidence in their VR abilities. The post-intervention fun rating (Post-Fun) had a very strong correlation with the post-intervention confidence rating (Post-Confidence, $\tau = .686$, $p < .001$), which was the highest correlation observed. This indicates that the fun experienced with VR post-intervention has a significant relationship with confidence in the technology.

Table 3.
Kendall's Tau-b Correlations Among VR Experience Measures

Measures	Pre-Interaction	Pre-Experience	Pre-Fun	Post-fun	Pre-Confidence	Post-Confidence
Pre Interaction	1.000	.300**	.240*	.321**	.269*	.304**
Pre-Experience	.300**	1.000	.462***	.280*	.655***	.326***
Pre-Fun	.240*	.462***	1.000	.536***	.569***	.426***
Post-Fun	.321**	.280*	.536***	1.000	.332*	.686***
Pre-Confidence	.269*	.655***	.569***	.332*	1.000	.438***
Post-Confidence	.304**	.326***	.426***	.686***	.438***	1.000

*$p < .05$. **$p < .01$. ***$p < .001$. $N = 64$ for all analyses.

NOTE. Pre-Interaction = "In general, how do you like to interact with new computer technology? (Pre)"; Pre-Experience = "What is your prior experience with VR? (Pre)"; Pre-Fun= "How fun do you think VR can be/is? (Pre)"; Pre-Confidence="How confident are you with VR? (Pre)"; Post-Fun="How fun do you think VR can be/is? (Post)"; Post-Confidence="How confident are you with VR? (Post)"

Overall, the correlations reveal that experience with, and attitudes towards, VR before an intervention is significantly correlated with post-intervention perceptions. Notably, fun and confidence with VR are consistently interrelated, both before and after the intervention, underscoring the importance of these affective factors in VR engagement and learning. The correlations between different measures of VR experience before and after an intervention provide insights into how these variables interact with each other.

The question was to investigate the impact of VR technology on engineering students' perceptions of fun and confidence within a machine design course. Results demonstrated that following the VR intervention, students reported a significant increase in both the perceived fun and confidence related to VR, with confidence showing a greater degree of increase. Correlation analyses further indicated that prior experience with VR and a general inclination to interact with new technology were positively associated with both pre and post-measures of fun and confidence. These findings suggest that the use of VR in educational settings positively affects students' attitudes towards technology, enhancing their engagement and potential learning outcomes.

Q2. Was VR combined with traditional instructional methods (VRTIM) more effective in increasing knowledge of specific machine elements when compared to traditional instructional methods (TIM) alone?

The efficacy of combining VR with Traditional Instructional Methods (VRTIM) as opposed to utilizing traditional instructional methods (TIM) alone was assessed in an evaluation study. Specifically, the study aimed to assess the impact of these teaching strategies on learning specific machine elements among students. The data were analyzed using a paired samples t-test to compare the pretest and posttest scores of two instructional conditions.

For the condition using VR (VRTIM), there was a statistically significant increase in the knowledge scores from the pretest (M = 2.81, SD = 1.48) to the posttest (M = 3.96, SD = 0.92); t (63) = 6.249, p < .001 (two-tailed). The observed mean increase in scores was 1.15 points (95% CI [0.78, 1.52]), which was found to be substantial. The effect size for this increase, calculated using Cohen's d, was 1.47. This large effect size suggests a considerable impact of the VRTIM approach. In contrast, the condition using traditional instructional methods alone (TIM) also showed a significant increase in scores, however to a lesser degree. The pretest scores (M = 2.33, SD = 1.31) compared to the posttest scores (M = 2.83, SD = 1.10) demonstrated a significant improvement; t (61) = 2.287, p = .026 (two-tailed). The mean increase was moderate at 0.44 points (95% CI [0.06, 0.82]), with an effect size of Cohen's d at 1.51. Despite being a large effect size, this increase suggests that while TIM alone can be effective, its impact is not as great as when it is combined with VR.

Table 4.
Effects of VR enhanced instruction in content knowledge learning compared to traditional instructional methods (0-6 scale).

Instructional Method	**Pretest Mean (SD)**	**Posttest Mean (SD)**	**Mean Difference**	**95% CI of Difference**	**t(df)**	**P (two tailed)**	**Cohen's d**
VRTIM	2.81 (1.48)	3.96 (0.92)	1.15	[0.78, 1.52]	6.249(63)	< .001	1.47
TIM	2.39 (1.31)	2.83 (1.10)	0.44	[0.06, 0.82]	2.287(61)	.026	1.51

*p < .05. **p < .01. ***p < .001. N = 64 for all analyses.

Note: VRTIM = Virtual Reality and Traditional instructional methods; TIM = Traditional instructional methods. The analysis involved 64 participants for Pair 1 and 62 participants for Pair 2.

Further, a repeated measures analysis of variance (ANOVA) was conducted to assess the impact of instructional method and time on participants' learning outcomes, as measured by test scores (Table 2). The within-subjects factors included two levels of time (pre, post) and two levels of instruction (VRTIM, TIM). The results indicated a significant main effect of time, F (1, 61) = 29.43, p < .001, suggesting a substantial increase in scores from the pretest to the posttest. Additionally, there was a significant main effect of instructional method, F (1, 61) = 26.21, p < .001, which indicates that the type of instructional method (VRTIM vs. TIM) significantly affected the scores. More importantly, the interaction effect between time and instructional method was also significant, F (1, 61) = 8.82, p = .004, indicating that the change in scores was different depending on the instructional method used. This interaction suggests that the combination of VR with traditional instruction methods (VRTIM) may have differentially impacted the score outcomes over time when compared with traditional instruction (TIM) alone.

As a result, these findings suggest that both time and instructional method significantly affected learning outcomes, with an interaction effect highlighting the potential benefits of integrating VR into traditional instructional methods. In summary, this question was to understand whether VR combined with Traditional Instructional Methods (VRTIM) was more effective in increasing knowledge of specific machine elements when compared to traditional instructional methods (TIM) alone. The findings from both the paired samples t-test and the repeated measures ANOVA provided a clear answer.

Table 5.

Repeated Measures ANOVA results by Time and Instruction

Source	**Sum of Squares**	**Df**	**Mean Square**	**F**	**p (two-tailed)**
Time	37.03	1	37.03	29.43	<.001
Instruction	36.78	1	36.78	26.21	<.001
Time * Instruction	6.83	1	6.83	8.82	0.004
Error (Time)	76.75	61	1.26		
Error (Instruction)	85.59	61	1.40		
Error (Time*instruction)	47.29	61	0.78		

Note. The degrees of freedom (df) reflect the within-subjects design. Partial eta squared values are included as measures of effect size.

The study's results indicated that VRTIM not only led to a significant increase in scores, reflected by a larger mean difference and a greater effect size than TIM, but also showed a significant interaction effect over time, which suggests that the learning gains with VRTIM are more pronounced than with TIM alone. Thus, the data supports the conclusion that VR, when combined with traditional instructional methods, is more effective for teaching specific machine elements than TIM alone.

Q3. Was VR combined with traditional instructional methods (VRTIM) more effective in increasing confidence pertaining to specific machine elements than traditional instructional methods (TIM) alone?

For confidence in the knowledge of machine elements (gear, bearing, and shafts), Table 6 shows a statistically significant difference ($p < .001$) between the pretest and posttest mean score. Specifically, there was an overall positive mean increase in students' perception of their confidence in the knowledge of machine elements (gear, bearing, and shafts) from before exposure to the virtual reality and traditional instructional methods (VRTIM) ($M = 3.41$, $SD = 2.00$) to after ($M = 6.41$, $SD = 1.53$). Also, Table 6 indicates that students' exposure to VRTIM largely improves students' confidence of their knowledge of machine elements (Cohen's d = 1.56).

For confidence in the knowledge of machine elements (screw, spring, and clutches), Table 6 shows a statistically significant difference ($p < .001$) between the pretest and posttest mean scores. Specifically, there was an overall positive mean increase in students' perception of their confidence in knowledge of machine elements (screws. Springs, and clutches) from before exposure to the traditional instructional methods (TIM) ($M = 3.61$, $SD = 1.95$) to after the TIM instructional mode ($M = 5.39$, $SD = 1.39$). Table 6 indicates that students' exposure to TIM largely improves students' confidence of their knowledge of machine elements (Cohen's d = 0.91).

Table 6 shows a statistically significant difference ($p < .001$) between gains in confidence of knowledge of machine element when exposed to VRTIM instructional mode and TIM instructional mode. Specifically, exposure to VRTIM instructional mode has a higher mean confidence gain in knowledge of machine element (*M* = 2.99, *SD* = 1.93), than exposure to TIM instructional mode (*M* = 1.78, *SD* = 1.96). Also, Table 6 indicates that the difference in confidence in knowledge gains of machine elements when exposed to VRTIM is moderate when compared to exposure to TIM (Cohen's d = 0.65).

Table 6.
Effects of VR enhanced instruction on gains in confidence about machine elements when compared to traditional instructional methods (0-10 scale).

	Mean	SD	SEM	T	df	p (two-tailed)	Cohen's d
Pre_VRTIM	3.41	2.00	0.24	12.55	63	<.001	1.56
Post_VRTIM	6.41	1.53					
Pre_TIM	3.61	1.95	0.25	7.23	62	<.001	0.91
Post_TIM	5.39	1.39					
Confidence gain in VRTIM	2.99	1.93	0.24	5.13	62	<.001	0.65
Confidence gain in TIM	1.78	1.96					

*p < .05. **p < .01. ***p < .001. N = 64 for all analyses.

Note: VRTIM = Virtual Reality and Traditional instructional methods; TIM = Traditional instructional methods.

Discussion

The findings from the series of analyses suggest several important implications regarding the use of VR technology in engineering education, particularly in a machine design course. First, the increase in students' perceptions of fun and confidence with VR, as evidenced by the descriptive statistics and the paired samples t-tests, implies that VR can be a powerful tool for enhancing the learning experience. The statistically significant increase in these affective domains indicates that the course with the use of VR can boost learners' confidence in interacting with technology, which is crucial for their engagement and the potential for deeper learning.

Furthermore, the repeated measures ANOVA reveals that students showed learning gains over time—evidenced by improved test scores from pre- to post-test. The type of instructional mode (whether the combined VRTIM or TIM only) did significantly impact these gains. This result is corroborated by the paired t-test result which provides evidence that students' knowledge of machine elements significantly increased during both types of instruction (VRTIM and TIM only). However, our Cohen's d result showed that students learned better during VRTIM than when TIM only was the mode of instruction. Our findings are consistent with literature that noted immersive VR as an effective pedagogical tool, which can enhance student learning in both the cognitive and affective domains [20].

Limitations

Since our work is an evaluation study, and not a research study, one of the limitations of the current study is the extent to which the result can be generalized. Also, this study faces a limitation of sample size. The sample size (n = 64) for this work is moderate. Furthermore, it should be noted that virtual reality technology is still being developed. Hence, the maximum impact of such a tool on the cognitive domain of learning might not be fully known as of now. Finally, readers should note that the virtual and traditional modes of instruction were on gears, bearings, and shafts, while the traditional instructional methods were on screws, springs, and clutches. A stronger research design will be a randomly assigned experimental study in which one group uses virtual reality on all the machine elements, and the other group is exposed to an alternative activity. Despite these limitations, this study provides valuable information on VR-enhanced learning during a machine design course.

Conclusion

In educating the future engineering workforce, it is essential that instructors leverage technology that will enhance visualization and aid interaction during learning. One of the challenges that engineering students face is being unfamiliar with machine components [21]. Our work on VR-enhanced learning is one of the several ongoing efforts to overcome this limitation. This paper presents a brief description of the immersive virtual reality technology developed by our team at Penn State for a machine design course. Also, presented is a comparative quantitative study of the impact of incorporating virtual reality into traditional instructional methods on student learning compared to using traditional instructional methods only in a machine design course. This study provides evidence that the use of VR increased students' perception of fun and confidence in using VR. Also, our study suggests that students' perception of their confidence in the knowledge gained and actual knowledge gained during the machine design was significantly higher when VR was incorporated into instruction. This suggests that leveraging VR in our machine design course has some educational advantages for undergraduate engineering students.

In the future, we will conduct a controlled study with additional comparative studies using a higher sample size with enough power to detect statistical significance. Also, we will be collecting, alongside the quantitative data, rich qualitative data that will deeply explore students' learning experiences when using VR technology. Furthermore, the research team will continue to work on the virtual reality technology developed for this course. Students' learning gains are expected to be higher when the VR technology is fully developed and deployed into the course. Finally, the authors hope that the fully developed VR technology for the machine design course will be inexpensive to acquire as a pedagogical tool.

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Appendix

Figures from Shifting Gears VR Application

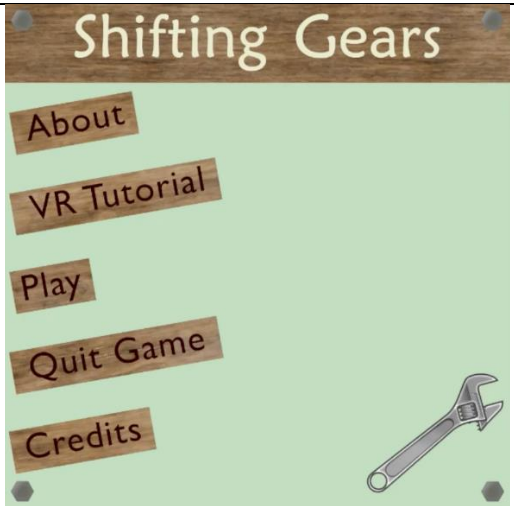


Fig. A.1. Game Interface.

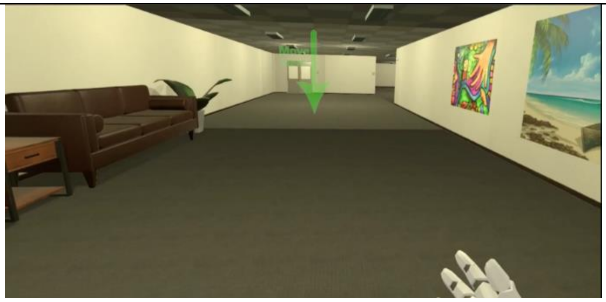


Fig. A.2. Entrance Hallway.

Fig. A.3. Initial View of Sorting Table.

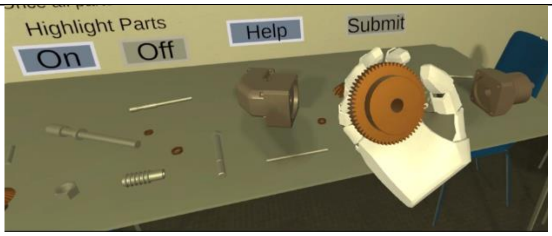


Fig. A.4. Player Inspecting Gears.

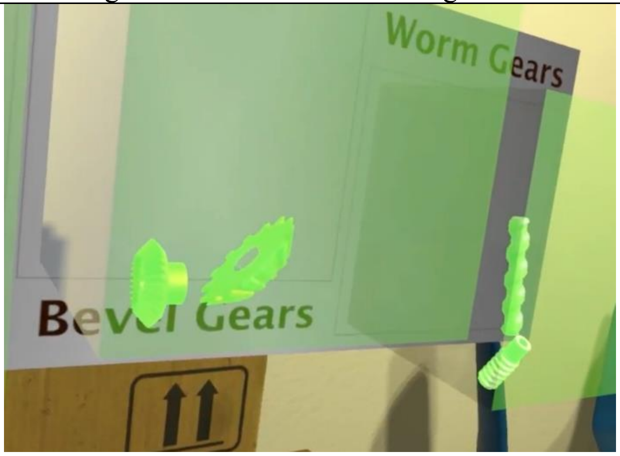


Fig. A.5. Player Sorting Gears.

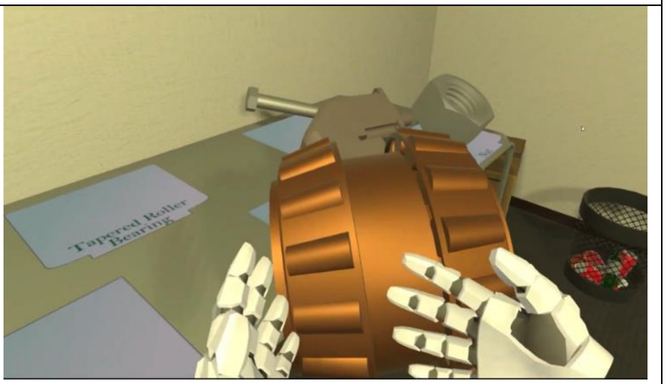
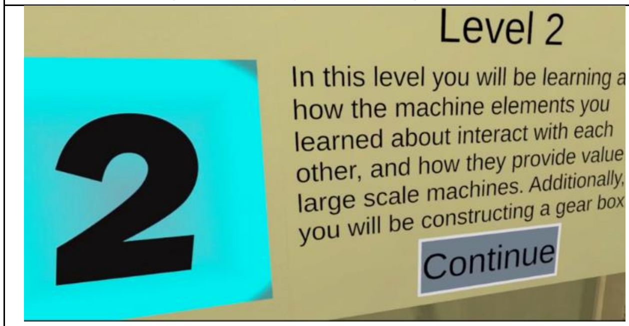


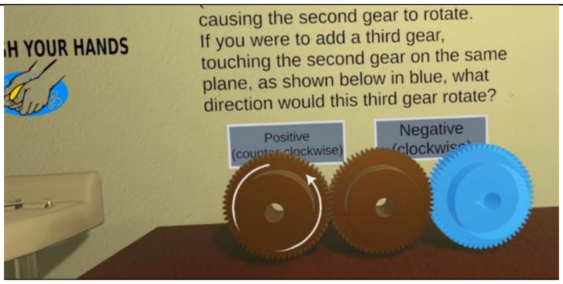
Fig. A.6. Oversized Bearing



Level 2

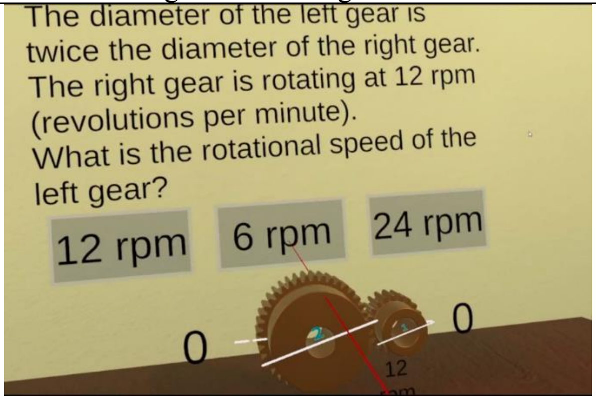
In this level you will be learning a how the machine elements you learned about interact with each other, and how they provide value large scale machines. Additionally, you will be constructing a gear box

Fig. A.7. Entering Level 2.



causing the second gear to rotate. If you were to add a third gear, touching the second gear on the same plane, as shown below in blue, what direction would this third gear rotate?

Fig. A.8. Rotational Direction



The diameter of the left gear is twice the diameter of the right gear. The right gear is rotating at 12 rpm (revolutions per minute). What is the rotational speed of the left gear?

Fig. A.9. Rotational Speed

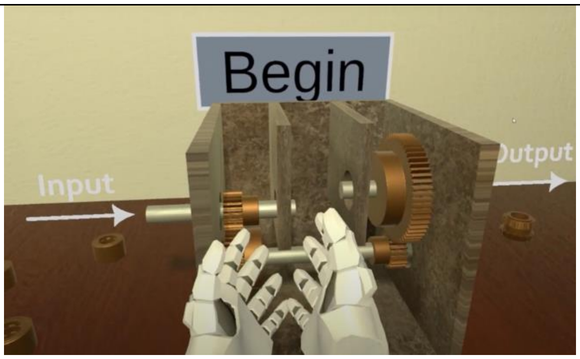


Fig. A.10. Gearbox