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Comparing the Effects of Two Active Learning Approaches*

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Theoretical and empirical studies suggest that learning is enhanced when instructors use pedagogical strategies that present information in multiple formats, and that such strategies engender more student engagement than passive lecture. Multimedia learning including multimedia-enhanced lecture (multimedia) and hands-on interactive group learning (hands-on) are two of such strategies that are believed to be more engaging than passive lecture. This paper describes a study in which hands-on with elements of other multimedia (or multimedia hands-on) and multimedia are compared. In a within-subjects experimental design, two groups (N = 19 in each group; hands-on and multimedia), alternated between being the control and treatment for either of two topics. Concept tests and worksheets were used to assess cognitive learning, and surveys for affective outcomes. The majority of participants agree that hands-on is more realistic and facilitates better cognition, professional preparedness, and acquisition of real-world experiences than multimedia. Surveys reveal high effect sizes in favor of hands-on. However, cognitive assessment scores did not produce any statistically significant differences between the two groups. No deleterious effects were perceived from hands-on and student comments suggest that it may be more beneficial than multimedia in terms of solidifying schema (longer term retention) and providing other benefits of competency-based education such as group skills, engaging learning and realism.

Keywords: student engagement; multimedia-enhanced lecture; hands-on learning; active learning

1. Introduction

Ongoing research on enhancement of cognitive and affective learning outcomes in Science, Technology, Engineering and Mathematics (STEM) is necessitated by educational stakeholders' concerns about declining achievement of learners especially in higher education, coupled with recruitment and retention of students in STEM disciplines [1–3]. For the engineering domain, the Accreditation Board for Engineering and Technology (ABET) has outlined criteria for important learning outcomes including the ability to apply STEM knowledge and identify, formulate and solve engineering problems [4]. Engineering education researchers have published studies examining different pedagogical practices that seek to demonstrate cognitive and/or affective benefits over lectures [5, 6]. These include pedagogical strategies that promote engagement [5] such as Problem-Based Learning (PBL) [7, 8], hands-on learning [9–14], interaction-enhanced lectures [6] and multimedia-aided deliveries [15–21].

Fink in his Significant Learning Taxonomy (FSLT) [22] identified three synergistic (non-hierarchical) cognitive dimensions important to learning: Foundational knowledge (F), Application (A) and Integration (I). A measurable enhancement in any of these dimensions suggests pedagogical effectiveness. Several studies have indicated that each of these cognitive dimensions could be enhanced by different pedagogical interventions. One approach is to use a student interactive strategy. For example, Dochy and colleagues in 43 medical classrooms [23] found that students who experienced project-based learning (PBL) showed better knowledge application outcomes than those who learned the same thing through lecture, with a weighted effect size of 0.46, while lecture was better but not practically significant for acquiring foundational knowledge, with a weighted effect size of 0.22. In this meta-analysis, PBL strategy included small group, student-centered, instructor-facilitated, authentic problem-driven learning, with plenty of self-direction. Another meta-analysis by the same authors found that PBL students performed better on the linking of concepts and principles, with a weighted effect size of 0.80, while lecture and PBL students performed similarly on understanding of concepts, with a weighted mean effect size of 0.07 [24]. Springer, Stanne and Donovan's meta-analysis [25] showed a higher cognitive outcome in a PBL small group over a lecture group in STEM disciplines (effect sizes: 0.51 for cognition, 0.55 for attitude and 0.46 for persistence). Prince's meta-analysis [26] showed that active learning outperformed lecture with effect sizes greater than 0.5 but

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cautions on the contextual limitations of their research in education (i.e. importance of study context, as it is possible that other trends could be found in different contexts). Hake's [27] and Redish's [28] studies stand out for using more than one measure to quantify cognition. Hake's study involving more than 6,000 students from 62 different introductory physics classes at different US Universities, Colleges and High schools found improved conceptual knowledge gains for interactive learning, where teams of two or more discuss and select from a list of multiple choice short answers to a conceptual prompt from the instructor, over straight lecture groups using the Force Concept Inventory (FCI) [29] and application of concepts using the Hestenes-Wells quantitative Mechanics Baseline Test (MBL) [30]. The average normalized pre to post gain on the FCI for the interactive group of 0.48 ± 0.14 ($N = 4{,}458$) was significantly higher than that of the more passive group with a gain of only 0.23 ± 0.04 ($N = 2{,}084$). The posttest MBL results were well correlated with the FCI scores with the interactive group doing better (average score of 60% vs. 40%). Redish reported learning gains for computer-based active-engagement tutorials over traditional tutorials using FCI as a test of foundational knowledge and a free-response question as a test of application of principles. The FCI pre-post improvement as a percentage of maximum possible gain for the tutorial groups on all questions was 52–77% while for the lecture group improvements for the same questions was only 11–48%.

In addition to collaborative learning, an instructor may add a hands-on approach. Brown et al. [31], comparing hands-on collaborative learning of concepts in open-channel flow using highly visual miniaturized desktop open-channels to lecture found that the former was better with an effect size of 0.98, $p < 0.05$. In another study, Burgher and colleagues found hands-on group learning helped more in learning at the higher levels of Bloom's taxonomy such as in evaluating, creating and applying, and was equally effective at the lower levels except on one question where lecture helped more with remembering foundational knowledge [32]. Linsey and co-workers in a Materials class found cognitive gains for lecture with hands-on over straight lecture with an effect size of 1.6 [33]. This result was augmented by a student survey which reported higher support for the hands-on exercise. Fernandez-Samaca and Ramirez [34] in several consecutive semesters of a Control Systems course reported higher outcomes for the hands-on group on both the fundamentals and analysis aspects of the course. The cognitive results show higher grade point averages for the hands-on group (fundamentals: $\mu = 3.65$, $\sigma = 0.45$, $N = 30$, analysis: $\mu = 3.77$, $\sigma = 0.37$, $N = 60$) over "classical" lecture (fundamentals: $\mu = 3.15$, $\sigma = 0.65$, $N = 64$, analysis: $\mu = 3.5$, $\sigma = 0.75$, $N = 75$). Surveys administered to examine students' perceptions on how hands-on contributed to learning and motivation showed very positive responses for both aspects of the course (motivation: 4.7 for hands-on and 4.15 for lecture, and contribution to learning: 4.5 for hands-on and 4.25 for lecture, out of a total score of 5). Abdulwahed and Nagy's study showed statistically significant performance with a treatment group (average score of 57%) which had a virtual laboratory preparation before a hands-on exercise compared to a control group (average score of 45%) that had the same hands-on exercise without the virtual pre-lab [35]. This suggests that the use of pre-lab preparation and hands-on experience might be a powerful synergistic strategy for learning.

One theory that has been used to explain findings in multimedia research is the dual coding theory, which posits that the human mind processes verbal and visual information using two separate and independent channels. The theory predicts that multimedia instruction consisting of verbal and visual components would make more efficient use of human cognitive architecture and lead to better learning [36]. For example, Downs et al. used lecture, iPod and computers to deliver materials on descriptive statistics in a 3×2 study [37]. They found that those who experienced dual mode presentations via iPod or computers had a test score average of 9.8 ± 0.3, which was significantly better than those who only had lecture with a test score average of 8.4 ± 0.4. Also, an audio/visual group (average score of 10.6 ± 0.4) significantly outperformed the audio/text group (9.0 ± 0.4) and the audio group (8.4 ± 0.4). Bond et al. [38] found improvement in self-reported cognitive and affective learning outcomes for a multimedia case study group over a discussion group. The multimedia group perceived a higher but statistically insignificant improvement in higher order cognitive skills, however they reported a statistically significant better attitude towards and perceptions of benefits of, engineering (effect sizes of 0.62 and 0.37, respectively at $p < 0.001$).

Some studies emphasize the importance of multiple measures in assessing pedagogical effectiveness. For example, Yadav and colleagues [39] found no difference in conceptual understanding in two mechanical engineering topics between case study and lecture students using a single concept score. However, a survey administered to the same students revealed that 79% believed that the cases added more realism to the class, 69% believed it was more thought provoking and 64% believed it was more relevant to learning the course concepts. Chenkin et al. [20] also found no statistically significant cognitive or affective difference between a web-based group who used online tutorials and a straight lecture group to learn a medical procedure, and hence the affective results confirm the lack of efficacy in this case. Another study by Damewood et al. [19] found no difference between a group that used a multimedia simulator and another which used a physical human model to learn skills on Focused Assessment with Sonography for Trauma (FAST). They did not, however, survey the two groups on their perceptions which would have been beneficial given the contrasting modes of learning. Seabra et al. [21] found no cognitive difference between students who experienced multimedia presentation via computer and students who experienced a straight lecture on the same urology topic. However, through survey responses, 74% of the multimedia group reported that an instructor is still important suggesting that multimedia presentation should be instructor-mediated. These studies demonstrate the importance of using multiple assessment instruments in determining the overall impact of an implementation as further insights are gained, albeit from self-report surveys or interviews. The use of multiple measures helps examine the robustness of findings across all measures.

In summary, there is strong evidence demonstrating the effects of learning with hands-on interactive or multimedia approaches over lectures.. Furthermore, where no statistical advantage in test scores is shown, the use of other measurement instruments may shed further light on relative advantages or reveal student consensus on what may be used to improve an approach. Some studies shed more light on learning gains through assessment of both cognitive and affective outcomes using multiple measures. Unfortunately however, many studies only report on one cognitive dimension using just one assessment instrument.

In the present paper, we report on the outcomes of a study where two different instructional designs, multimedia and lecture (control), and multimedia and hands-on (experiment) were used to teach two crucial Fluid Mechanics and Heat Transfer (FMHT) topics: the shell-and-tube heat exchanger (shell-and-tube) and a new spring water-air cross flow system [40], used to demonstrate evaporative cooling concepts, that we call the evaporative cooling heat exchanger (evaporator). Although it is reported in extant literature that these two pedagogies engender better learning outcomes than straight lecture, it is not yet known how they compare to each other in the engineering education domain. We seek to answer this overarching research question:

> What are the effects of learning with a hands-on active strategy with some multi-media aspects compared to a multimedia-aided lecture?

The processes in the instructional designs, the assessment artifacts or tests, and assessment approaches are described in light of corresponding underlying theories with a view to discerning factors responsible for any differences in cognitive and affective outcomes.

1.1 Human cognition, multimedia learning and motivation

The human cognitive architecture (HCA) model, a postulate of how the human mind works, consists of a vast long-term memory (LTM) which is analogous to the hard drive on a computer and the limited short-term or working memory ("central processing unit"), which is the center of task execution. The LTM contains disjointed facts and poor schemas for novices, and sophisticated schemas (highly organized cognitive structures like concepts and skills) analogous to "neat" folders for experts. Additionally, schemas no matter how complex can be stored in working memory as a single unit and will become automated with continuous usage. When faced with a task, information can pass into working memory through the LTM and/or the senses analogous to a keyboard (sensing) communicating information to a hard drive [41] with the flow process more efficient for experts. The limitations of this central executive for novices, necessitates effective instructional design to bridge the gap. In other words, effective instructional design that enhances schema construction should serve as the central executive, or basis on which task execution protocols are built, for the novice.

The Baddeley model [36] divides working memory into two independent subsystems: the visuospatial which processes visual (written text and pictures), spatial and haptic (tactile/ kinesthetic) information; and the phonological which processes auditory (narration, environmental sounds and music), signs and lip reading information. It also proposes episodic buffers such as smell and taste that mediate between the two subsystems. These subsystems are believed to be independent because deficiency in one is not compensated for by the other [42]. Complementary to this theory is the generative theory of multimedia learning; one of its main postulates being dual-coding which posits that verbal and visual information are *processed* in separate but interconnected systems. The other is the dual-channel which posits that visual and verbal information are *perceived* in different subsystems. A useful principle (the multimedia principle) that stems from these theories is that more learning will occur when material is presented in formats that use both auditory and visual subsystems (i.e. multimedia) than by a format that uses either in isolation.

Multimedia learning refers to learning with multiple representations of the learning materials of interest including words (narrative and written), pictures (movies, images, sketches, simulations, schematics, charts) and physical models (prototypes and equipment). Because the two working memory subsystems which process visual and verbal information are independent and complementary [36], presenting information in both modes avoids overloading one subsystem and thus makes more efficient use of the working memory for more efficient cognition. Also, because multimedia messages may appeal to a wider range of learning styles than single media, well-designed multimedia instruction should increase learner engagement and motivation [43–45].

Mayer et al. [46] outlines a general cognitive theory of multimedia learning (CTML) and principles of multimedia learning for different domains of learning. There are three basic underlying assumptions of this theory namely: the dual-channel assumption (auditory and visuospatial channels), the limited capacity assumption (human limits of simultaneous information processing by each channel), and the active processing assumption (humans actively process sensory inputs in these two channels and integrate with prior knowledge from long-term memory to construct new knowledge). Stimuli gathered from multimedia presentations are transformed into representations by either or both channels and in some cases cross-channel representation of a single sensory stimulus is possible (dual-coding [47]). The major postulate of the CTML is that multimedia instructions that are designed in consideration of how the human mind works are more likely to lead to meaningful learning, which impacts the solving of new problems (transfer of knowledge).

These CTML principles are especially important to the largely physical engineering domain. Intuitively, the static structure of an engineering system will be better represented by an iconic diagram rather than just a verbal description while a dynamic process will be better represented by an animation [46]. Both of these representations are usually mediated using written words (annotations) or spoken words (live instructor or computer speakers). Furthermore, these representations could be two or three dimensional. It is also possible to use physical models of different magnification. These could be static physical models like parts of equipment, cadavers or miniaturized equipment. It could also be a 'live' representation such as a swinging pendulum or a true-sized/miniaturized multicomponent dynamic process. The important question here is which representation or set of representations is most effective for significant learning that includes near and far transfer and soft skills development? The answers to this question are not trivial and can only be articulated by careful empiricism.

1.2 Hands-on learning, cognition and motivation

Hands-on-mediated instruction is believed to enhance both cognitive and affective outcomes in various learning domains mainly because it fosters authentic learning or realism. In a study using simulation and hands-on equipment to teach a computer architecture class, Heise [48] found a large improvement in test scores and improvement in motivation for the hands-on class over the simulation class. This was attributed to more time spent on hands-on projects by the students because of increased interest, the euphoria of building something that works, a sense of contribution within groups, metacognition or self-awareness of one's own knowledge from instructor feedback, and the increased capacity for transfer due to a more flexible representation of knowledge. This type of instruction is especially important in engineering because of its inherent experiential nature.

Kolb's experiential learning model is particularly applicable to hands-on or experiential learning [49] and is depicted in Fig. 1. It suggests that significant learning is more likely to take place when a person goes through a cyclical process of a new concrete experience, such as being introduced to a new piece of equipment or process, followed by a reflection on that experience which then leads to abstract conceptualizations and generalizations which are tested empirically, and which in turn leads to another new experience.

1.3 The Purpose of this Study

The present study extends previous research discussed above in two important ways. First, we used a more robust and complete suite of outcome measures including foundational knowledge, i.e., a recall measure, application, and integration, i.e., transfer measures, as well as open-ended survey responses to examine the effects of learning. The use of transfer measures and open-ended survey

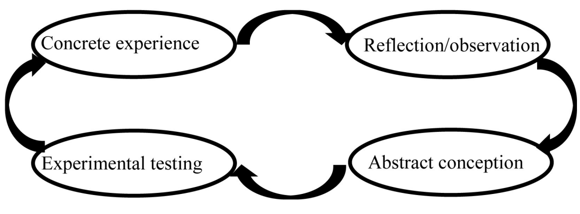

Fig. 1. Schematic of Kolb's model [49].

responses are an important addition as previous research mostly used recall and other measures that do not adequately assess application and integration of the concepts learned. Transfer measures typically require learners to integrate the information learned in the lesson and apply the newly acquired knowledge to solve novel problems [46]. Second, unlike previous studies of active learning in engineering education, the present study is grounded in the cognitive theories of learning and thus the study is well positioned to advance theory. We argue that the possibility of making both empirical and theoretical advancements is another major contribution of the present study.

2. Methods

The study methodology employed in this research is grounded in the cognitive theory of multimedia learning and Kolb's experiential learning theory and the results are interpreted from these theoretical standpoints.

2.1 Participants and study design

The participants consisted of 38 chemical engineering juniors (10 females and 28 males) from a large public university in the U.S. Pacific Northwest. They were split evenly into two groups consisting of 19 participants each, having balanced GPAs and alternated between the control (multimedia) and experimental (hands-on) groups for shell-and-tube, and evaporator topics. The treatment group was split autonomously (p 75–76 of ref [50]) into 5 subgroups of 3 and 1 subgroup of 4 for the social construction of cognition built into hands-on active learning, a subset of the pedagogy package dubbed CHAPL (Cooperative Hands-on Active Problem/Project-based Learning) [51–53]. Anonymity was maintained in rating by assigning codes to the participants. The names associated with these codes were unknown to the raters.

2.2 Procedure

The two DLM cartridges shown in Fig. 2, a shell-and-tube, and an evaporator, (developed on an NSF project for bringing research into the classroom [40]), were selected for probing associated learning outcomes. These topics are particularly rich in concepts, and foster use of design and analysis skills of importance in chemical engineering practice.

The outcome of interest is growth in the three cognitive dimensions of FSLT [22], Foundational knowledge, Application and Integration (F, A, and I). Coded ~5 min pre- and post-quizzes, worksheets and exam questions were rated using a new Fink rubric [54] to examine differences in cognitive dimensions. Also, a survey in a Likert format [55], including questions on the degree to which specific topics presented through hands-on or multimedia impacted or would have impacted growth in the Fink dimensions, was administered. The survey also included questions on the degree to which the implementations used the 7 Principles of Good Practice in Undergraduate Education [56]. Non-parametric Wilcoxon statistical analysis [57], and written comments were used to assess perceptions about the relative value of the approaches.

Table 1 summarizes the main concepts for each topic while Table 2 outlines the implementation.

2.3 Design of assignments

Assignments were based on the principles of authentic assessment [7], designed to elicit responses revealing students' understanding or lack thereof, and reflect the Fink cognitive dimensions, **F**oundational knowledge, **A**pplication and **I**ntegration [22] (see Table 3). Quizzes consisted of conceptual questions expected to elicit answers that are proxies for competency in these dimensions.

2.4 Design, development, and deployment of rubric and associated assessments

Our scoring rubric (Table 4), detailed in ASEE

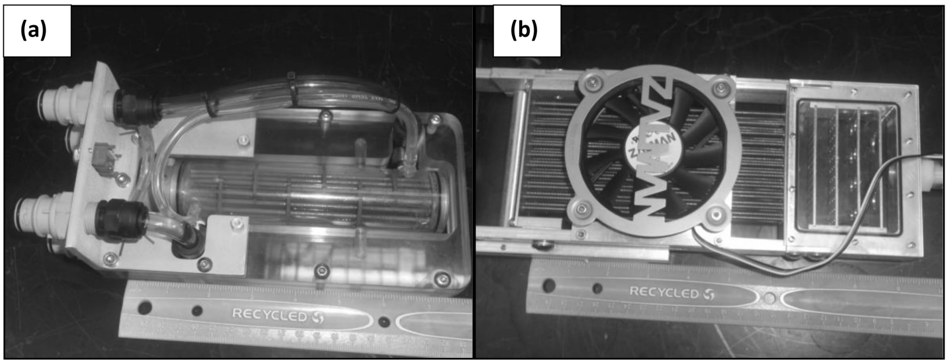

Fig. 2. DLM cartridges used to teach both topics (a) 1-shell pass, 2-tube pass heat exchanger (b) Evaporator (array of springs with fan blowing air across).

Table 1. Major Shell-and-tube and Evaporator concepts

Shell-and-tube	Evaporator
1. Thermal resistance, overall heat transfer coefficient	1. Thermal and mass transfer resistances, mass/heat transfer coefficients
2. Equipment architecture and its influence on individual heat transfer coefficients	2. Equipment architecture and its influence on the heat transfer coefficient
3. Hydrodynamic and thermal boundary layers	3. Hydrodynamic, thermal and mass transfer boundary layers, wet & dry bulb temperatures, relative humidity, psychrometrics
4. Shell-and-tube design/optimization	4. Evaporator design/ways of improving heat transfer

Table 2. Pedagogical implementation

Topic	Multimedia Lecture	Hands-on
Shell-and-tube	Individual 5–7 min Shell-and-tube pretest (one week prior) Individual 5–7 min Evaporator pretest	Individual 5–7 min Shell-and-tube pretest (one week prior) Individual 5–7 min Evaporator pretest
	43 min Shell-and-tube lecture Realistic Shell-and-tube data given 3D animation of 1–2 Shell-and-tube (architecture & flow pattern) 2D diagram of a 1–2 Shell-and-tube & 2D of a U-tube exchanger Picture of industrial scale Shell-and-tube Picture of Shell-and-tube cartridge Shell-and-tube analysis	10–13 min pre-lecture 3D animation of 1–2 Shell-and-tube (architecture & flow pattern) Picture of industrial scale shell-and-tube Picture of Shell-and-tube cartridge 25–30 min activity Groups manipulated controls & took measurements while discussing worksheet conceptual questions with instructor facilitation
	Individual 5-min posttest on Shell-and-tube	Individual 5-min posttest on Shell-and-tube
Evaporator	~50 min: Evaporator worksheets handed out with realistic data Basic geometry & flow patterns of cooling towers Photos of industrial scale cooling tower flow pattern Photos & 3D CAD drawing of Evaporator cartridge Theory & analysis of cooling towers: enthalpy balance/ geometric parameters Details on how to use psychrometric charts	~ 15 min: Geometry & flow patterns of cooling towers Photos of industrial scale cooling tower flow pattern Briefing on experiments 20–25 min 3-member groups performed experiment & discussed worksheet with instructor facilitation ~ 10 min analysis lecture: enthalpy balance/ determining geometric parameters Very brief instruction on using psychrometric chart (due to time constraint)
	Individual 5-min posttest on Evaporator	Individual 5-min posttest on Evaporator

Table 3. A brief description of Fink's cognitive dimensions

Dimension	Description	Example
Foundational knowledge **F**	Knowledge and understanding of principles and relationships between them; recall of models; significance of parameters	Recalling & understanding terms in the energy balance, correctly defining and understanding physical significance of parameters
Application **A**	Using principles to explain observed physical phenomena; solve particular problems; critical, creative & practical thinking	Reducing the general energy balance to suit a particular problem; using signs & other professional conventions; critical analysis
Integration **I**	Connecting principles within a domain (intra-domain) or connecting principles across different domains (inter-domain)	Connecting flow, heat & mass transfer and economics; Reynolds number determines flow regime used to select the Nusselt number correlation

conference proceedings [54], was based on Fink's cognitive dimensions and principles of rubric design [58, 59]. The development and deployment of the rubric was done using Belfer et al.'s moderator-facilitated convergent participation model (CPM) [60] and the Educational Testing Service's criterion of at least 70% inter-rater agreement (IRA). Gains from rubric assessments were tested for statistical significance. The percentage gain was computed as:

$$Gain = \frac{Post\ Score - Pre\ Score}{Maximum\ Score} \times 100$$

2.5 Inter-rater agreement

Pre-norming IRAs between paired raters of 67–100% on 25% of the assignments were achieved and increased to 83–100% after norming, which meets the Educational Testing Service criterion. High initial values indicate raters were well trained in the deployment of the rubric since they were familiar with it from a previous study [54] and suggest an objective, reproducible and reliable scoring process was conducted. One of the raters proceeded to rate the remaining assignments.

3. Results and discussion

3.1 Cognitive gains

Post-instructional gains in cognition were assessed by tracking improvements in test scores. Scatter plots of the pretest and posttest Fink's dimensions for the two groups were plotted to visually depict any differences. Figs. 3 and 4 are the scatter plots for the Shell-and-tube and Evaporator concept tests. These figures show that the data are concentrated to the left of the horizontal axis showing that the majority have low average pretest scores, below the MCL of 3, indicating both groups had inadequate schemas in their long-term memory (LTM) or low prior knowledge from previous experience to answer the questions adequately. It should also be noted that the points on the scatter plot appear to be less than the N in Table 5 because some of the data points coincide where a student's pretest and posttest scores are equal. Also, the scatter plots shows that quite a few of the points are above the 45 degree line which indicates improvement from pretest to posttest (points on this line indicate no improvement and points below indicate negative improvement). Fairly similar trends are observed from these plots with individuals generally improving with 58–91% of the posttest scores above pretest scores for most indices. Exceptions however occur for the Evaporator Application dimension for multimedia (42%) and Integration dimension for hands-on (46%). It is also observed that 55–92% of the students at least attained our significant learning benchmark or MCL of B– (3.0). Exceptions however appear again in all cases for the Evaporator A and I dimensions with a mere 23–50% reaching the MCL in either teaching mode. This could be because the Evaporator is a new topic and materials for it cannot be found in texts or web resources. The relatively low scores on the Evaporator concept questions, with >50% below the 3.0 bench mark, and seemingly persistent misconceptions, such as misunderstanding of the significance of the wet bulb temperature, noted in learners' responses allow room for further investigation into plausible reasons and ways to overcome them. It could be that some of these concepts need a more cogent visual reinforcement or that more time is needed.

Further analyses of the results were done to elucidate the statistical significance of the improvements in performance shown in the scatter plots. Table 5 presents t-test results at a 5% error rate. First, we observe insignificant differences for both

Table 4. Exerpt from the Fink's rubric [72]

<table>
<tr><th></th><th colspan="11">Score Levels (Significant Learning Anchor = 3 or B-)</th></tr>
<tr><td>Scores</td><td>0</td><td>0.5</td><td>1</td><td>1.5</td><td>2</td><td>2.5</td><td>3</td><td>3.5</td><td>4</td><td>4.5</td><td>5</td></tr>
<tr><td>Letter grades</td><td>F</td><td>D</td><td>D+</td><td>C-</td><td>C</td><td>C+</td><td>B-</td><td>B</td><td>B+</td><td>A-</td><td>A</td></tr>
<tr><td>Rubric dimension</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td>Foundational knowledge
Recall basics i.e.:

words/definitions / equations / principles / concepts/ relationships/ logic / understanding

Show understanding via explanations, rationale for choices</td><td colspan="2">No Evidence of correct definitions / equations

Explanations incoherent & obviously have no bearing on knowledge of FMHT principles

Linkage between parameters in explanation is confusing / inarticulate explanation</td><td colspan="2">Evidence of sketchy, disjointed explanations of FMHT principles

Equations incomplete/inconsistent with system, dimensional inconsistency

Patchworks of correct ideas, sometimes contradictory (e.g., opposite ideas on the same principle in different parts of problem; correct in one sentence and wrong in the next)</td><td colspan="2">Evidence that equations/explanations of FMHT principles appear correct but lack enough substance to be considered complete

Equations essentially complete but lack some significant terms</td><td colspan="2">Evidence that equations/ explanations of FMHT are coherent and reasonable but lacking finishing or contain some slight error (mathematical or 'minor' conceptual flaws)</td><td colspan="3">Evidence that equations / definitions complete and correct

FMHT explanations / principles complete & perfect; thorough understanding of foundational principles as evident from explanations / usage of models / drawings</td></tr>
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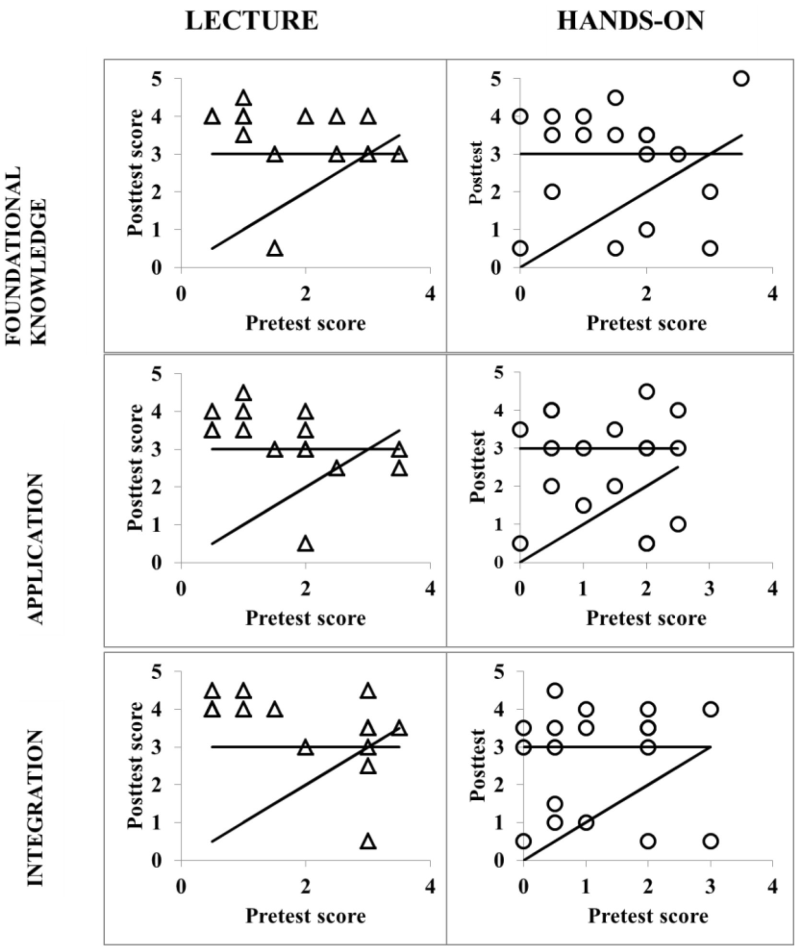

Fig. 3. Shell-and-tube posttest vs. pretest scores. Most of the students are above the equality line (45 degree diagonal) signifying improvement, and at or above the horizontal minimal competency of 3 (B-) for both the lecture and hands-on groups.

instructional groups on the Shell-and-tube and Evaporator pretests further suggesting both groups had similar prior knowledge in these domains and are cognitively matched. We also observe that both groups improved on posttests and final exams over pretests. However, as shown in the table, these differences are insignificant which suggest, on average, similar cognitive growth. The only exception is a decrease in Integration scores for both groups in both topics on the posttest. This may be attributable to the lack of sufficient time (5-minute posttest) to properly articulate and integrate the concepts learned. An analysis of the results for the final exams reveals that while there are minor losses in Foundational knowledge and Integration in particular for the shell-and-tube between the posttest and final, there are gains across the board for the Evaporator. This suggests that the students have had more time to digest this new material during subsequent interactions with the instructor and their preparations for the finals. It is expected that students will spend more time practicing skills on topics they perceive to be more difficult and thereby build better understanding on such a topic.

Given that learners in the two groups started out at the same point on the cognitive trajectory (comparable pretests), we can safely assume that the material on the posttest will present the same intrinsic cognitive challenge and therefore the same performance only if the two different instructional interventions gave rise to the same level of working memory management [61, 62]. This suggests that both groups, on average, encountered all the elements of cognition and their interrelatedness necessary for answering the questions in such a way that cognition is indistinguishable by the tests and rubric. The collective working-memory effect [63] suggests that collaborative learning is more efficient for high complexity tasks because of the distributive potential over many working memories. The authors however hasten to caution that if a member has highly defective schemas or the group is not functioning properly, these can inadvertently lower the sum of the working memory capacities akin to the expertise reversal effect [64], leading to

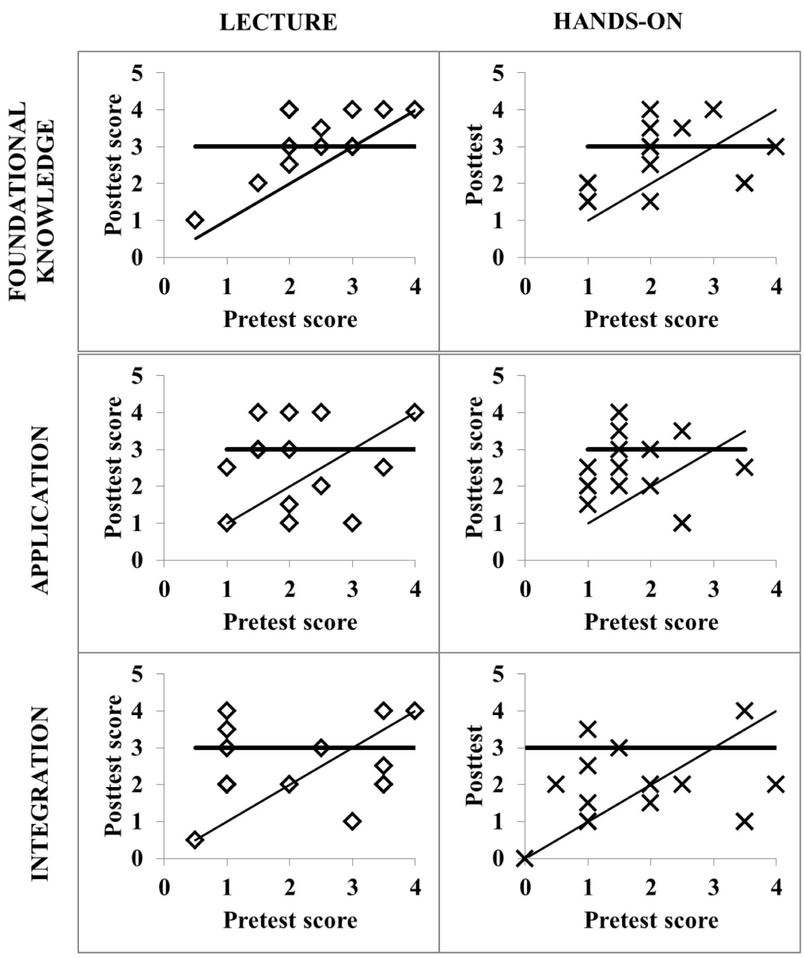

Fig. 4. Evaporator posttest vs. pretest scores. The data points above the equality line (the 45 degree diagonal) indicate improvement. Fewer students reach minimal competency of 3 (B-) than for the Shell-and-tube.

lower performance. The collaboration effect is expected to be more significant when solving complex problems, in situations of far transfer (contexts different from practice contexts [65]) and for high road transfer (contexts needing a metacognitive effort and an active search for connections [65]). One such context would be the design of a shell-and-tube heat exchanger to achieve a particular heat duty or the design of the unit of a processing plant for cooling a given product. It is therefore expected that tests designed to measure short or medium-term, near transfer (similar contexts) such as in this case, would mask the collaboration effect. Another, though affective explanation for the collaborative effect is that learners in a group reported less mental effort expectations while learners who expected to do it alone reported the opposite [66]. This suggests that the former category already had a higher expectancy of task-related efficacy which provides higher motivation to succeed and results in higher metacognitive effort in doing their own part of the work. This argument and the 'flat' intergroup performance profile, suggests that the tasks inherent in the tests used in this study may be of inadequate complexity to make efficient use of the added collaboration or 'distributed working memory' in the experimental group. It would be interesting to compare individual design submissions from collaborative teams to that from individuals in a multimedia-aided lecture. The authors note that the distributed memory advantage is used in most professional settings especially in engineering and hence the usefulness of inculcating collaboration in engineering education for authenticity and fostering of team skills.

Further analyses of answers to related questions in the final examination written two months later also revealed no overarching significant intergroup differences suggesting the groups on average had acquired the same near-transfer, and medium-term cognitive retention capacities. Instructional implementation notes reveal both groups were given PowerPoint presentations (simultaneous imagery and narration) of the architecture, principles, and

Table 5. Percentage gains showing statistically insignificant differences ($0.14 \leq p \leq 0.97$) at 5% error rate for the Fink cognitive dimensions

Shell-and-tube	Multimedia: M (SD), %				Hands-on: M (SD), %			
	N	F	A	I	N	F	A	I
Pre/Post	15	32 (31)	30 (33)	32 (39)	18	26 (36)	24 (32)	29 (34)
Pre/Finals	16	24 (23)	28 (26)	23 (33)	17	25 (28)	29 (27)	26 (29)
Post/Finals	17	–13 (23)	1.5 (31)	–6 (35)	19	–8 (23)	2 (31)	–3 (36)
Evaporator								
Pre/Post	15	26 (23)	11 (50)	–3 (60)	15	3 (57)	13 (53)	–23 (84)
Pre/Finals	15	22 (23)	24 (25)	24 (35)	18	10 (26)	14 (20)	7 (28)
Post/Finals	14	11 (27)	15 (27)	16 (32)	15	3 (26)	3 (27)	11 (29)

Note that N is different and less than 19 in most cases because computations were done only for students who completed both the pretest and posttest.

processes involved in the Shell-and-tube and Evaporator. The experimental group however had the PowerPoint presentation for a shorter time using the rest of the time for student-student, student-DLM and student-instructor interactions. It is therefore possible that both groups apprehended the cognitive elements required to tackle the tests nearly to the same degree during the PowerPoint presentation, and thus the 3D imagery and animation, flow of water, fan blowing, and change of physical variables on screen, and more animated discussion with peers and instructor, were redundant [62, 64, 67], or that the hands-on group had partial grasp of content from the PowerPoint and only an equal grasp as the control group after subsequent hands-on collaboration. Future research may examine this further. It is also noteworthy that 78% of the cognitive outcomes from the final examination were above the MCL of 3 suggesting that both instructional designs created significant learning [22] even though it is difficult to isolate the contribution of each from these assessments. It is also possible that accretion to the long-term memory from other sensory information (such as websites and texts) in the intervening weeks before the finals could have played a crucial role in working memory management.

Table 6 shows several worksheet questions and one final exam question in which the multi-media rich lecture group significantly ($p < 0.05$) or nearly significantly ($p < 0.1$) out-performed the hands-on group and in which large effect sizes were found. In these few instances where results support stronger cognitive gains through multimedia lecture the findings are not surprising as the learned attributes relate to factual knowledge, a list of steps provided to students on optimizing a heat exchanger, a formula given in class (and not found in any textbook) for Evaporator surface area, a demonstration of how to use a graphical solution approach and a thorough lecture (more time) about design changes for enhancing heat exchange. Even though no between-group difference was found in the cognitive results, the lack of statistical significance could be as a result of several factors including low power because of small number of participants involved in the study ($14 < N \leq 19$).

The tentative statistically similar intergroup results in this study is consistent with results from previous studies [19, 20, 38, 39]. Similar to these studies, we surveyed the students to investigate their perceptions of the differences between the two pedagogies and how it impacts their learning.

Table 6. Analyses where Multimedia appeared advantageous

Question nature	Dimension	Hands-on M (SD)	Lecture M (SD)	p; Effect size
Shell-and-tube Worksheet: Advantages of a double-tube pass Shell-and-tube?	A I	1.4 (1.1) 1.1 (1.1)	2.1 (1.2) 2.2 (1.4)	0.07; – *0.01; 0.89
Shell-and-tube Worksheet: Economic tradeoffs in optimization?	F I	2.5 (1.1) 1.9 (1.2)	3.2 (0.9) 2.6 (1.1)	0.05; – 0.09; –
Evaporator Worksheet: Water surface / unit volume of fill material.	F	3.0 (1.3)	3.7 (0.8)	0.07; –
Evaporator Worksheet: Compare correlated to experimental heat duties.	A	3.0 (0.9)	3.6 (0.8)	0.05; –
Shell-and-tube Final: Enhancement of shell-side heat transfer coefficient?	A	2.3 (1.4)	3.3 (1.1)	*0.04; 0.81

* Effect size is meaningful only for cases where a significant difference ($p < 0.05$) is found.

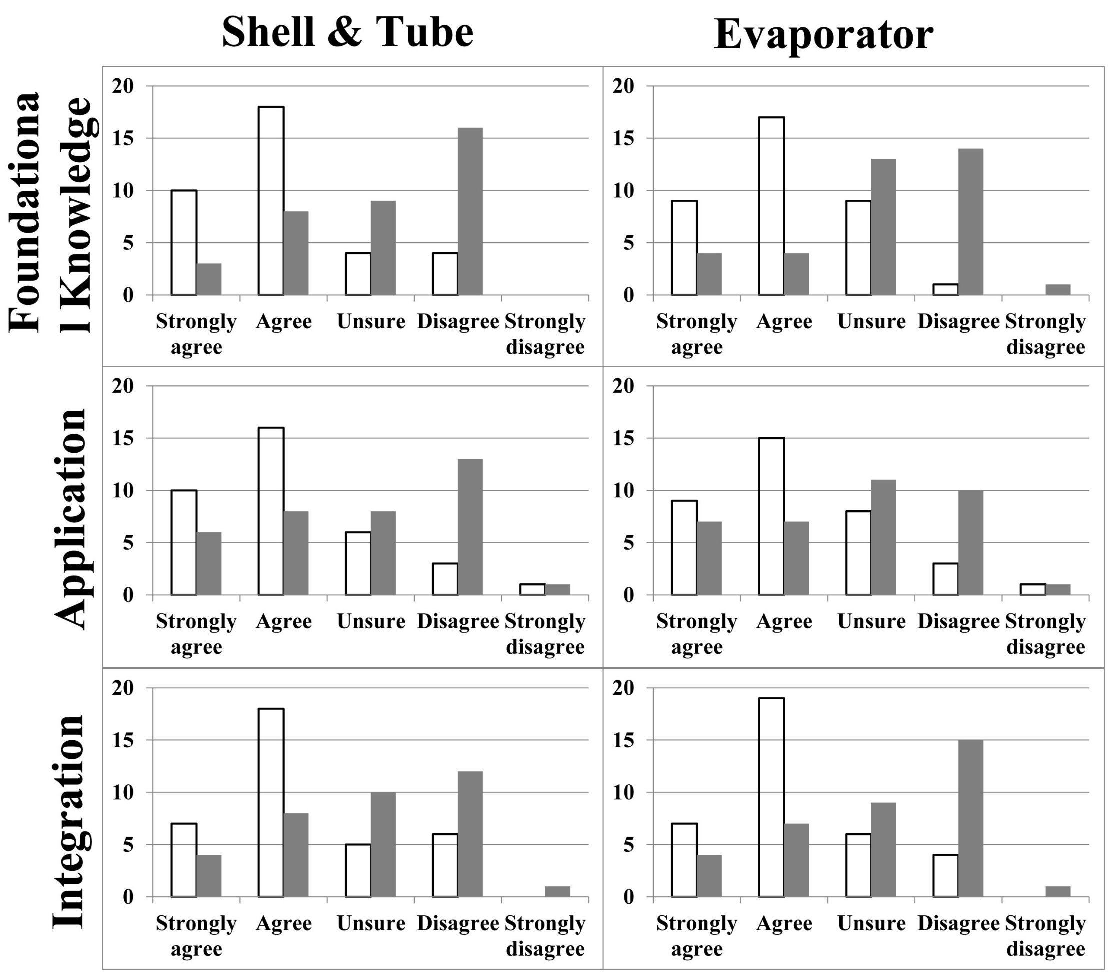

Fig. 5. Surveys on the three cognitive dimensions.

3.2 Self-report gains

Experiential hands-on and collaborative learning have been reported as creating longer-term retention and transfer than narration-based pedagogies [49, 66, 68]. To elicit student perceptions on how the pedagogies influenced their cognition in the Foundational, Application and Integration domains, survey prompts were designed and administered. Fig. 5 shows students perceive better learning from hands-on group learning than lecture for both topics. Table 7 presents a nonparametric statistical Wilcoxon signed-rank paired difference test done by allotting numerical values for the Likert-type responses. To reduce bias, converse prompts were given, e.g., 'Hands-on group learning (or Lecture) helped /would have helped more than lecture to understand the basic principles of Shell & Tube heat exchangers'. The large effect sizes of 0.8 to 2.0, and p-statistics < 0.05 (except in one instance where $p = 0.09$), indicate that students significantly perceived better learning from the hands-on group learning than from multimedia-enhanced lecture for all cognitive dimensions probed. An analysis of the free response data yields insights into students' perceptions that fall into three basic categories each addressed in the following sections. We hereby notice significant relative advantages of the hands-on aspect that are not revealed in the cognitive gains analyses.

3.3 Visual reinforcement of cognition

The responses to: 'Contrast your learning from lectures with that from the other activities (hands-on, group work and demonstrations)', showed a mix of perceptions from those solely in favor of hands-on (50%) through mixed (hands-on and lecture equally useful and complementary, 31%) to those solely favoring lecture (19%). Respondents in favor of hands-on had a variety of reasons the most prominent of which pertained to the visual and tactile reinforcement of cognition such as "I thought overall the hands-on was better because you were able to actually see and make connections on how the module worked." This statement could be interpreted as evidence that the student believes a visual learning experience helped understanding

[48]. Another said: "In lectures you learn the concepts and the mathematical reasoning behind the project but you never gain a sense of its applicability. In the activities everything is much more free form and as an individual you have to reason out why things happen the way they do and so you gain a *more solid* understanding of the concepts." This student seems to believe process visualization leads to better metacognitive processing and retention of schemas. Also the perceived 'applicability' from the hands-on could increase motivation as the student sees the value of the activity, a position consistent with Heise's findings [48]. Furthermore, 64% of the students responded that Hands-on helped with application. In a related prompt, 53% of respondents said lecture helped most with foundational knowledge. Yet another student said: "It was very evident that the activities helped 'stick' the information in my head. Being a 'tinkerer' it was a very natural learning method". This student is alluding to his belief that hands-on is in sync with his learning style (active learning) [69]. Other reasons alluded to the group dynamics, analytical skills, and active learning. It is interesting to note that most of the factors alluded to have been identified as part of competency-based education [67]) which the university engineering programs accreditation body ABET has continued to emphasize [2].

Respondents favoring a mixed approach suggested lecture was a necessary complement to hands-on. One participant said: "I think demonstrations and hands-on are just as important as lecture. They both have their place. Hands-on is good because you get a better idea of what the physical significance of the calculation is. But lecture is important because theory is explained, trains of thought are explained and calculation is outlined." Another wrote: "I learned a lot from the lectures. Though seeing what actually is going on when using the modules helped a lot." Still another: "Lectures taught me the equations and principles, activities helped me understand the knowledge more deeply and to be able to use it again." These students seem to be alluding to lecture being better for presentation of facts and procedures while hands-on grounds these cognitive elements in real life. This position is buttressed by Gijbel et al.'s meta-analysis of literature on Problem-based learning (PBL) and lecture which found that lecture students had slightly better basic knowledge than PBL students [24].

About 19% of the responses showed a marked lecture preference while still acknowledging how hands-on activities enhance their learning. One reads: "I preferred the lecture over the hands-on. I work better with multiple examples and in-depth explanations. Having a demonstration solidified the information that was taught via lecture." Another wrote: "I feel that the lectures helped me to understand the fundamental principles governing heat transfer more thoroughly; whereas the hands-on activities did not seem to be as well rounded and I had trouble converting the understanding I gained from the hands-on stuff to other systems. I would much prefer the lecture over the hands-on. Bringing in modules did help though and should be included with the lecture." These statements allude to this students' learning style preference (intuitive and verbal) [69]. However, it has been reported that most learners tend to be more visual than verbal [69], a finding attested to by this survey – about half were attracted to visual and other elements of the hands-on learning while the other half are distributed between the other learning styles. Also, all these statements did suggest that lecture was more appropriate for understanding the fundamentals or the Fink's Foundational knowledge dimension.

Interestingly, the words 'stick', 'solid', 'solidified' and other synonyms used by over half of the survey participants in reference to hands-on and demonstrations suggest long-term retention of the learned information which has been identified as the key objective of instruction [41]. While it is acknowledged that both pedagogies take advantage of the dual coding and dual channel theories [42], by using multimedia presentations, it appears students are more attracted to the haptic (tactile/kinesthetic) component as advanced by Baddeley's visuospatial model [36], which was evident more in the hands-on. It is not unreasonable therefore to state that students perceived better retention when a physical model is involved and principles are put into practice as it was the case during the deployment of the DLMs.

3.4 Metacognitive processing

A further analysis shows on average that about 80% of respondents were affirmative (~20% "strongly agree" and ~60% "agree") that hands-on group learning encouraged them more than lecture to answer their own questions for both the Shell-and-tube and Evaporator activities while ~10% were neutral ("unsure") and ~10% "disagree". These responses suggest the hands-on activities encouraged students to develop metacognitive skills or active processing which in the long run helps them to be better learners [48]. Also, 89% responded affirmatively (56% "much more" and 33% "somewhat more") when asked if the Shell-and-tube worksheet was more beneficial to their learning than textbook problems on the same topic, ~2.5% responded that it didn't make any difference ("the same") and 8.5% said it was less beneficial (6% "somewhat less" and 2.5% "much less"). Responses

Table 7. Wilcoxon analysis of class survey (Nw's [statistics in brackets] are calculated after excluding data for students who picked the same option for hands-on and lecture)

Dimension & topic	**Hands-on better** $N = 36$	**Multimedia better** $N = 36$	**Wilcoxon test**		**Effect size (Cohen's *d*)**
	M (SD)	*M (SD)*	*P*	N_W	
F Shell-and-tube	3.9 (0.9) [3.9 (0.9)]	2.9 (1) [2.7 (0.9)]	<0.001	31	1.3
F Evaporator	3.9 (0.8) [4.0 (0.7)]	2.9 (1) [2.5 (0.8)]	<0.001	25	2.0
A Shell-and-tube	3.9 (1) [3.8 (1)]	3.1 (1) [2.9 (1)]	0.03	28	0.9
A Evaporator	3.8 (1) [3.7 (1)]	3.3 (1) [2.9 (1)]	0.09	24	0.8
I Shell-and-tube	3.7 (0.8) [3.7 (1)]	2.9 (1) [2.8 (1)]	0.04	29	0.9
I Evaporator	3.7 (1) [3.8 (0.9)]	2.9 (1) [2.6 (1)]	0.01	28	1.3

on the Evaporator worksheets were also quite similar. Following are typical responses:

> "It was more interactive so it made it easier than textbook problems."
>
> "Worksheet was well organized. I can just follow the problem in the worksheet and understand the concepts easier."
>
> "Took you through the steps to solve the problem in an understandable way."
>
> "The worksheet broke it down easier and in a clearer way. It helped walk you through the necessary steps whereas the book usually throws the whole problem at you all at once."
>
> "Compared to McCabe (the required text), the worksheet broke things down more and was more theoretical which helped in the learning process. McCabe's problems usually feel too hard to learn with."
>
> "The worksheet was a more practical approach and made more sense intuitively than the book problems."

Responses suggest that worksheets, designed and developed as a complement to hands-on pedagogy, gave students much needed guidance in constructing their own cognition (scaffolding and cognitive apprenticeship [70]). The worksheets foster a completion effect [41, 71] by essentially outlining and starting the solution to the problem for the learner to complete. Completion of problems is also believed to be important for schema construction [67].

3.5 Collaborative, real-world advantage

Aside from F, A and I, hands-on is believed to impact other important areas of competency-based education, notably group dynamics and ill-defined problem solving. This is achieved by creating a collaborative environment and assigning semi open-ended group projects at the end of the class. In response to a prompt about professional preparedness, ~83% agree they felt more prepared (53% "much more" and 30% "somewhat more") for work in the field because of their experiences:

> "Group work is good for preparation for professional practice, because almost all companies have employees work in groups. This makes the work go faster and allows for different points of view."
>
> "Working as a group helps develop team work and leadership skills. Hands-on will prepare us for possible career circumstances where we actually have to troubleshoot a real system based on data and not just plugging numbers into given equations. The project was also very insightful by giving introductory understanding of a simplified design."
>
> "Since I learned the material better with the hands-on work I feel more comfortable telling a future employer that I know how to design heat exchangers."
>
> "From my experience, the lecture environment is going to be the least common activity in our future careers but hands-on work, group work, projects and demonstrations will be our primary duties during our professional practice."
>
> "They emphasized the applicability of the concepts learned in lecture and showed how things work on the macro scale. A person can do all the simulations he wants in the virtual world but it won't help get a feel of how things work in real life and that's what the hands-on group work really gets at."

In over 70% of the comments students say they appreciate analysis of real systems [48] used in professional practice and the role of hands-on in building their skills. They believe such learning solidifies schemas [67] and collaboration will certainly be a part of their professional duties [68, 72].

Because of students' positive opinions in the survey, the likelihood of type II error or false negatives in the cognitive data cannot be overlooked i.e. that the conceptual assessments cannot establish a difference that actually exists. The probability of making this error can be reduced by increasing the statistical power of the test such as by making the sample size as large as possible. This can be achieved by involving participants from other institutions or other disciplines that have FMHT in their curricula. Even though the logistics and cost of such an endeavor make it marginally attractive, the rich demographic data potential (for instance gender and academic major data) is likely to offset these considerations. Albeit, at the very least, a prior power analysis with inputs such as the kind of data tests to be used, the expected effect size and the allowable error rate, can be done to determine the minimum sample size required to obtain the usually-reported effect size in studies of this nature.

4. Conclusions and recommendations

Two pedagogies, a multimedia-aided lecture (control) and hands-on group learning with some brief multimedia interspersed (treatment) were used to teach two topics—Shell & Tube and Evaporative Heat Exchangers with one group used as the control in one experiment and as treatment in the other. Results showed no significant difference in rubric-generated cognitive outcomes, suggesting both pedagogies generated similar levels of working memory management. The relative statistical impotence due to the low N could have masked the differences and therefore it would be interesting to repeat the study with a large number of participants. It is also possible that the hands-on active tasks in this study were of inadequate complexity relative to participants' positions on the cognitive ladder to make efficient use of group working memory distribution in the treatment group. Perhaps examination of a more complex task like the design of a heat exchanger for a particular heat duty will yield significant between-group differences. It would be interesting to examine how individuals who have had hands-on collaborative instructions perform compared to individuals who have had multimedia lectures on a complex task. Is it possible that the former group has built up adequate schemas in long-term memory as a result of the collaborative working memory advantage during instruction to post better individual performances on the task?

Interestingly, an analysis of the survey responses reveals that students' significantly prefer hands-on. Written responses suggest this is related to their learning preference (>50% visual), beliefs that physical experiences lead to better metacognition, more robust and/or permanent retention, and appreciation of other skills such as learner centeredness, group dynamics and solution of ill-defined problems, demanded by current competency-based paradigms. This gives further impetus for studies with large N.

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