A Longitudinal Study of the Impact of Curriculum on Conceptual Understanding in E&M

S. J. Pollock

Department of Physics, University of Colorado, Boulder, CO 80309-0390

Abstract. We have collected extensive data on upper-division Electricity and Magnetism (E&M) student performance at CU Boulder since we introduced the University of Washington's *Tutorials in Introductory Physics* in 2004 as part of our freshman curriculum. In the earliest semesters, all upper-division students had themselves taken a non-Tutorial introductory Physics, providing a baseline at this upper-division level surprisingly close to post-scores in our reformed introductory course. More recently, the population in the upper-division is mixed with respect to freshman experience, with over half having been taught with Tutorials as freshmen. We track those students and find that on average, their individual BEMA scores do not change significantly over time. However, we do find a significantly stronger performance at the upper division level for students who went through Tutorials compared to those who had other introductory experiences, and stronger scores still for students who taught in the introductory sequence as Learning Assistants, indicating a long-term positive impact of Tutorials on conceptual understanding.

INTRODUCTION

In Fall 2004, we introduced the University of Washington's (UW) *Tutorials in Introductory Physics*[1] into Physics II (Electricity and Magnetism, E&M) at the University of Colorado (CU). There is considerable published evidence regarding the efficacy of Tutorials[2-4], and we use the BEMA (Brief E&M Assessment)[5] as one of a set of measures of student learning. Since relatively small amounts of BEMA data have been published elsewhere, we simultaneously collected data from upper-division students to provide a CU baseline. We assumed upper division physics majors could provide a reasonable target goal for learning in our large introductory class.

We find several interesting results regarding the development of student understanding of E&M concepts, as measured by the BEMA. We do *not* observe much change in performance for individual students over the 2+ year period between when they complete Physics 1120 and when they complete either first or second semester upper-division E&M. We *do* see evidence that the addition of Tutorials has had a significant impact (statistically and pedagogically) on student performance on this instrument at the upper division. We also see further evidence of the benefits of undergraduates serving as teachers (the CU Learning Assistant, or LA, model [6]).

STUDENT POPULATIONS

Physics 1120 is the introductory Calculus-based second term course on E&M at CU. The class serves engineers (who dominate the class by number), physics majors, and a variety of other hard-science majors. Class size ranges from ~325 to ~475. The basic course structure and content has not changed in many years, but in Fall 2004, traditional recitations were replaced by UW Tutorials[1]. A more detailed description of the transformed classes at CU can be found in our earlier work [3-4]. Phys 1120 classes are taught by different faculty every term, but almost all these faculty regularly used *Peer Instruction*[7] in the large lectures (with clickers), computer-based homeworks[8], and a staffed help-room. The primary curricular switch which occured in Fall '04 was the addition of Tutorials with trained undergraduate Learning Assistants [6].

Physics 3310 and 3320 are CU's upper-division physics majors' E&M sequence, with an average of ~30 (in 3320) to ~40 (in 3310) students. A few students in these classes are e.g. astrophysics or engineering majors, but the large majority are junior physics majors. The textbook for many years has been Griffiths[9]. The course is taught in a very traditional physics lecture style by a variety of different faculty.

MEASUREMENTS

The BEMA[5] instrument has been given at the start and end of Physics 1120 every semester since we began using UW Tutorials, on paper, during the first and last weeks of the term. We obtain matched, valid (e.g. most questions attempted, not all answers the same, etc) pre/post scores for ~70% of students. In the upper division courses, students were asked only at the *end* of the semester by their instructor to take an online version of the BEMA. This voluntary approach resulted in a smaller fraction of returns, approximately 45%. However, average course grades for the students who took the BEMA online are statistically indistinguishable from the remaining students.

DATA AND RESULTS

The Physics 1120 data were collected primarily to evaluate the impact of our curricular reforms, with results in progress and reported elsewhere [3,4]. Here we are interested in the longitudinal aspect, an evaluation of the difference in BEMA results between introductory and upper-division students, and the change over time of students' scores on this instrument. We present some of the principal results, first for the two classes separately, then examining longitudinal effects more directly.

Introductory Physics 1120

The average BEMA *pre*score in Phys 1120 has been stable for six terms at 26+/-1% (with stand. dev. ~10%). Posttest scores range from 50-60%, (s.d. ~15%). The average for all students in the first three terms of data collection was 56% (and it is a small fraction of *these* students who fed into the upper-division courses for which we have data, as described below.) The correlation coefficient (r) of BEMA post-score to course grade ranges between .55 and .65 for different terms. We are not aware of many published BEMA results to calibrate these results, but the BEMA is difficult - our incoming graduate students average just over 80% on it. The authors of the BEMA[5] indicate that these prescores are typical, and that our postscores are well above what might be expected from a purely traditional introductory lecture course.

Upper Division Phys 3310 and 3320.

For the first three terms (Fa04 to Fa05) that we gave the BEMA to upper-division students, none had themselves gone through an introductory course with Tutorials. Thus, we have baseline data for how upper division physics majors with a mix of introductory

courses (but none with Tutorials) performed on this conceptual exam *after* upper-division E&M. Average results were stable from term to term; there do not appear to be any systematic instructor effects. Average upper-division BEMA scores are 54+/-2% (s.d. = 19%) for N=76 unique students over those 3 terms, representing ~45% of all enrolled students. This is our "control" group, shown on the left in Fig 1. Note that this average score is marginally *below* the postscore we obtained after our freshman level course with Tutorials, a result we found somewhat surprising, and discuss below.
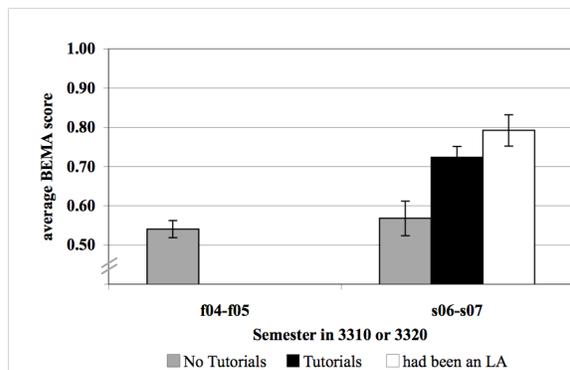
FIGURE 1. BEMA scores *after* upper division E&M, separated into terms in which no one had been through freshman Tutorials (grey, far left), and terms (right) in which some students had not been through freshman Tutorials (grey), but others had (black). The last (white) bin shows students who had been LAs for Phys 1120. Error bars are standard error of the mean.

Starting in Sp06, the upper-division population changed - some students came up through the usual sequence from a freshman Tutorial experience, while others did not. This latter group included e.g. students who passed out of freshman physics due to AP credit, transfer students, and students who took extra time to go through the sequence. Because of this diverse population, the first question we wanted to answer was whether the subpopulation of upper division students without Tutorial experience had a different BEMA score than the control group from earlier terms. The answer was essentially no. The average BEMA for Sp06-Sp07 for the "non-Tutorial experience" students was 57+/-4% (s.d. = 21%) (N=23), see Fig 1. Recall the control group of upper-division students from earlier terms had an average BEMA of 54%. So, although the "non-Tutorial" subgroup demographics differs over time, their BEMA scores are not statistically significantly different.

We now consider the scores for upper-division students who *did* come through freshman Tutorials. The results are also shown in Fig 1. These students (middle bar on the right of Fig 1) have an average

BEMA score of 72+/-3% (s.d.=15%) (N=33), statistically significantly higher than their non-Tutorial compatriots in the same courses, and/or the control group of *all* upper-division students from earlier terms. This is one of the central observations of our study - it appears that the Tutorial experience leads, after several years, to more than a 15 point difference on the BEMA, comparing to either students in the same classes, or to the earlier upper-division control group who never had Tutorials as freshmen. This difference is statistically significant (p<.01, 2-tailed t-test), and pedagogically significant (effect size > 0.75)

The final bin in Fig 1 shows BEMA scores for students who taught as Learning Assistants in Phys 1120 at some point between taking freshman physics and taking Phys 3310. Their BEMA in 3310/20 is higher still: 79+/-4%, (s.d.=12%), but the small number (N=7) is subject to larger fluctuations - indeed, one poor student had a strong impact on this group, most had extremely high BEMA scores. We do not include the LAs in our pool of "Tutorial" students in Fig 1, due to their extraordinary additional contact with the material, but these data provide additional evidence for the impact of teaching experiences for undergraduates [6]

A final question on the online BEMA asks students to tell us how hard they tried. Counting *only* students who said they tried "very hard" (just under half the students who took it), the results are consistently shifted up by 5-10 points, but this does not change the qualitative results or *differences* between the groups discussed above. LAs all indicated they had tried very hard, perhaps an interesting observation itself.

Some of our more traditional faculty have explicit course goals in 3310/20 which are far from the sort of elementary conceptual understanding addressed by the BEMA. They often have a highly mathematical and quantified problem-solving focus. One can therefore ask about course grades in the upper-division courses as determined by these faculty. The average course grade is quite consistent over time (close to 3.0, "B-centered"). For the students in the control group (everyone in both 3310 and 3320 from F04-F05) (s.d.=0.8). For students in the "No-Tutorials" subgroup in S06 through S07, the average course grade was 3.0+/-0.1 (s.d. =0.7), further evidence that this subgroup is not so different from the earlier control group. All "No-Tutorials" students combined (both courses, all six terms of the study) have an average grade of 3.04+/-0.07 (s.d.=0.8, N=124). For the "freshman Tutorial" subgroup, the average course grade was 3.3+/-0.10 (s.d=0.7, N=40), statistically significantly higher than students without Tutorials (p<.05, 2-tailed z-test) The average grade in 3310 and 3320 for the 7 students who had been LAs was 3.2.

The students with Tutorial experience thus had marginally higher course grades than the cohort in the *same* semesters who did not have a Tutorial background, and also higher than the control group of all students from earlier terms, but the difference is not great. Nonetheless, one certainly cannot argue from this data that our increased focus on conceptual development at the freshman level is *harming* our upper division majors by any of these measures, as at least a few traditional faculty seem to fear.

Direct Longitudinal Comparisons.

The data above indicates several long-term benefits of having taken Tutorials as freshmen, both in BEMA scores and possibly course grades. But what is the direct impact of Phys 3310 or 3320 on student conceptual understanding?
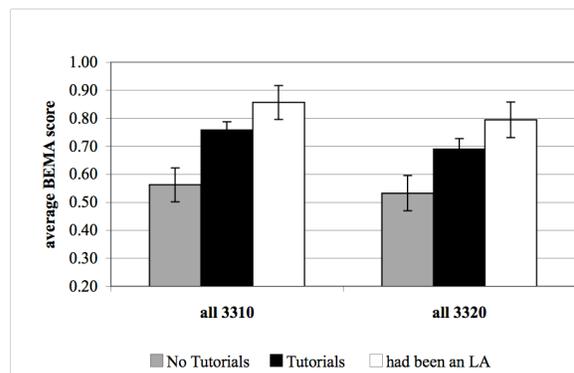
FIGURE 2. BEMA scores in upper division courses, separated into Phys 3310 (E&M I) and 3320 (E&M II) Errors are standard error of mean.

In Fig 2, we separate the results from Physics 3310 and 3320. The leftmost bin for each class combines students from early terms (none of whom had Tutorial experience) with the sub-population in later terms who also had no Tutorial experience (since we saw above there was little difference in these groups' scores or grades). We see a very slight, but not statistically significant, decline in BEMA scores from 3310 to 3320. One might wonder about "exam fatigue", but only 39 students took the BEMA in *both* 3310 and 3320, and for these students, their average *shift* in BEMA score from 3310 to 3320 was 0.0% (s.d.=15%). It appears that Phys 3320 does not have any measurable positive impact on conceptual understanding of freshman-level material. Fig 2 shows that the difference of Tutorial and non-Tutorial students persists even after 2 semesters of upper division physics, and that the LAs remain stronger as well.

Table 1 (below) allows a comparison of average scores on "clusters" (3-8 questions per category) of BEMA questions taken by upper-division students at the end of the course. Even when looking at different conceptual categories, the UW Tutorials appear to have a significant positive residual impact on students.

TABLE 1. Comparison of performance of upper-division students on groups of BEMA questions.

Rough category of BEMA questions	No 1120 Tutorial	Had 1120 Tutorial (and prior BEMA score in Phys 1120)
• E-fields, Gauss, and Coulomb	71%	86% (84%)
• Fields in Matter	50%	72% (72%)
• Current and Voltage	56%	72% (74%)
• Circuits	40%	60% (75%)
• Magnetostatics	62%	83% (80%)
• Faraday's law	28%	41% (45%)

The "no Tutorial" column consists of N=98 individuals, combining the control group with any later students who had never taken freshman Tutorials. Standard errors of these entries vary, but are typically +/-2%. We have no 1120 BEMA data for this population. The "Tutorial" group (last column in Table 1) has N=33 students. Standard errors vary by category, but are typically +/-3%. As in Fig 1, we do not count scores a second time if a student takes the BEMA in Phys 3310 and again in 3320, nor do we include students who had been a Learning Assistant.

We were able to track some individuals from Phys 1120 through upper division. The numbers in parentheses in the 2nd column of Table I are older data from when the students had originally taken the BEMA at the end of Physics 1120, for the (N=29) students for whom we have these matched data. There is little change over a 2-year period, on average, with only one category (circuits, the BEMA topic perhaps least likely to be revisited in upper-division) showing a statistically significant drop.

Recall that the overall average BEMA score in Phys 1120 in the semesters we're considering was 56%, but the average score for the 29 students who would ultimately take Phys 3310 and 3320 (later in their careers) was 74%. (Their score *in* 3310/3320 would become 75%) It appears, then, that our future physics majors are already doing well above average in their introductory course as freshmen, and retaining their skills years later.

CONCLUSIONS

Upper division courses *by themselves* do not appear to have much impact on BEMA scores, evidenced by direct measurement of shifts (or lack thereof) for individuals taking the BEMA before and after either upper division course. However, we do measure a significantly (>15%) higher BEMA score in 3310/20 for the student population who went through freshman Tutorials, along with a marginally higher course grade.

It is interesting to speculate about the origin of these strong differences in the upper division populations. UW Tutorials do not directly address all of the particular topics and questions on the BEMA, although there is considerable overlap, nor are they typically quantitative. Tutorials focus on conceptual understanding, sense-making, and explanations, which appears to manifest itself in improved performance on this conceptually focused exam. Apparently some of the qualitative understanding built at the introductory level persists over time, and benefits students at the upper division level, as evidenced by improved BEMA scores and (marginally) improved grades. We also see continuing evidence that the LA experience is beneficial. We believe such data are of value to PER researchers trying to understand mechanisms and outcomes of reformed curricula such as the Tutorials, and also to traditional faculty who are trying to decide on the value (and perceived costs) of such curricula.

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