Learning Gains with the Newton's Third Law Open Source Tutorial in Austrian High Schools

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Abstract

In her MS thesis, the first author researched the use of the Newton's Third Law Open Source Tutorial in Austrian high schools in order to see if students achieve a better conceptual understanding of the physics concepts, compared to traditional instruction. The research was carried out in nine classes from three different schools (a total of 240 students). Pre-post testing was done with a "Force-Test" that included the Force Concept Inventory's Third Law dimension. All classes had already had their lessons in mechanics by the time of the pre-test. Therefore, the pre-tests results presented a good picture of what students had learned with traditional instruction. Between pre- and post-tests students had their normal classes with traditional instruction, which did not include mechanics, and only one 50-minute intervention with the Open Source Tutorial on Newton's Third Law. Subsequently they had the post-test, which showed what they learned with the tutorial. The results' analysis shows an evident gain on conceptual understanding of Newton's Third Law's concepts (g-factor=0,45). The survey also indicated that these concepts actually made sense to the students: many of them had reconciled their intuitive ideas with the correct scientific concepts.

1. Motivation and Introduction

Physics instruction in schools is important on the individual scale, as it can provide a student with knowledge and problem solving skills that can positively impact their future career and general well-being. Physics instruction is also important on the collective scale, as these influences on individuals further impact social, political, economic and cultural worlds. Awareness of the role that learning (or failing to learn) physics has on society has motivated the past decades of physics education research, which has examined how students learn, and what are better ways to teach. This body of research has demonstrated that teaching physics in a traditional didactic (lecture-based) manner is ineffective, both in terms of learning gains and in terms of student enjoyment of and interest in the subject. Teachers can not “spread knowledge” the way one might spread fertilizer over a field. Students do not passively absorb knowledge; their interaction with each other and with the content material is crucial to their learning. Research has shown that for most students to learn beyond an extremely superficial level, it is necessary for teachers to provide opportunities for those students to actively participate in the classroom. This is true not only for developing conceptual understanding of physics content (e.g., Newton’s laws of motion). This is also true for improving students’ attitudes and views about the nature of physics knowledge and about what it means to acquire physics knowledge (that is, a student’s “epistemology”). Many teachers (implicitly) assume that it can help students learn about the nature of physics by making side remarks like “see, this model is useful not only in the idealized no-friction world, but in the real world outside the classroom too!” Research has shown, however, that this is just as feckless as lecturing about Newton’s laws: “spreading fertilizer” on students, either in the form of content knowledge or epistemological knowledge, is rarely effective (Schecker et al. 2018).

Students' epistemology is important, because it can influence the way students prepare for classes and their self-evaluation of how well they “know” the material being taught. Research has shown that students' epistemology in physics correlates with their interest in physics, with the courses they choose to take, with conceptual gain in those courses, and with the decision to become a physicist (Hull et al. 2016). Researchers have also found a positive correlation between epistemology and performance motivation of students (highly motivated adolescents have more expert-like views about the nature of science knowledge and learning) (Urhahne and Hopf, 2004). Epistemology is important not only at the level of the individual, but also at the level of a democratic society, since people's perception of science affects both the financial support given to scientific research (Hull et al.

2016), and also the degree to which government officials place their trust in scientific findings. In times of crisis, like what the world currently faces with the COVID-19 pandemic, we can clearly see the importance of such trust.

Many instructors assume that students will develop a more expert-like epistemology automatically as they learn the content taught in class. Research has shown, however, that this is generally not the case, even in courses that use research-based curricular materials in an active learning environment to promote conceptual understanding. In fact, unless the physics instruction explicitly embeds epistemology into the curriculum, it is most common for student epistemology to become less expert-like after the instruction (Hull et al. 2016).

According to Elby (2001), "so many excellent physics courses fail to foster significant epistemological change," even courses that include some elements with focus in epistemology. He argued that "isolated pieces of epistemologically focused curriculum aren't enough. Instead, the epistemological focus must suffuse every aspect of the course. Therefore, the instructor's commitment to an epistemological agenda must go beyond a willingness to implement certain curricular elements… [there is] no reason to think that partial adoption of [a suite of curricular elements demonstrated to improve epistemology] will lead to epistemological change."

The course Elby described in his article utilized guided worksheets ("Open Source Tutorials", or OSTs) that students complete in groups. OSTs emphasize not only conceptual growth of learners around unintuitive physics topics, but also epistemological development, by having learners come to see that their intuitions can align with physics. Elby is the founder of the OSTs concept, and a suite of OSTS was developed at the University of Maryland, College Park. Our research investigates the effectiveness of OSTs with Austrian high school students.

After Elby's words of caution, there have been occasional reports of instructional interventions that saw improvement in student epistemology despite not having "the epistemological focus… suffuse every aspect of the course." (e.g., Hull et al., 2016; Wilhelm, 2006) As such, to date, there remains work to be done to examine what the necessary conditions are for epistemology to improve (Hull et al., 2016). We hence decided to evaluate not only students' conceptual learning gains, but also changes in student views about the nature of physics knowledge and learning, despite our intervention being limited to implementation of just one OST, covering the topic of Newton's Third Law.

2. Newton's Third Law and Open Source Tutorials

Although students in beginning physics classes often see much of the physics they learn as being vastly disparate from the "real world" outside of the classroom, Newton's Third Law (N3) seems particularly "against common sense". The law concerns the interaction between two objects: "To every action there is always an opposed equal reaction", or "Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first" (Hewitt, 2015).

Smith and Wittmann (2007) analyzed student reasoning about N3 in various contexts that they categorized as pushing situations and collision situations. These two types of situations are distinguished by the period of time in which the two bodies are in contact. While collision situations happen when the bodies interact for a very short period of time, pushing situations are when the objects are in contact for an extended period of time. They found that, for both types of situations, student reasoning is affected by contextual factors such as the velocities and masses of the two objects (students have no difficulty, for example, thinking that equal mass objects colliding with each other at equal speeds exert equally large forces on each other. In cases where one of the two colliding objects begins at rest and has less mass, on the other hand, student thinking is much less likely to align with N3). Smith and Wittmann categorized these context-based subtleties in student reasoning with three facets of reasoning:

a) action dependence facet (the more active or energetic object exerts more force);

b) mass dependence facet (the bigger or heavier object exerts more force);

c) velocity dependence facet (the moving object or a faster-moving object exerts a greater force) (Smith and Wittmann, 2007).

Students may also use two or all three of these facets simultaneously in thinking about a given problem. For example, in the situation of a more massive object smashing into a smaller-mass, stationary object, all three facets might be elicited. On the other hand, students may produce a false positive (giving the correct answer with incorrect reasoning) because of different facets compensating each other (for example, students may say that the forces are equal if a lighter object crashes into a slower object). Smith and Wittmann (2007) found that the action dependence facet was the most common incorrect reasoning used by students in their study (e.g., if A hits B, A exerts a force on B. B does not exert a force; it is just in the way).

It is important for instructors planning and teaching lessons on N3 to consider how students reason about the topic and to be aware of what epistemological implications their instruction may have. Specifically, the three facets of reasoning mentioned above seem sensible to students, so teachers should be very careful when teaching about N3 that student epistemology does not deteriorate; namely, students generally walk away from learning about N3 with a stronger feeling that physics doesn't make sense except, perhaps, to physicists. Just as important as this pedagogical content knowledge is curricular knowledge, being aware of what curricular materials have been developed that teachers can take advantage of to guide their students to conceptual change and the feeling that the physics they are learning can make sense.

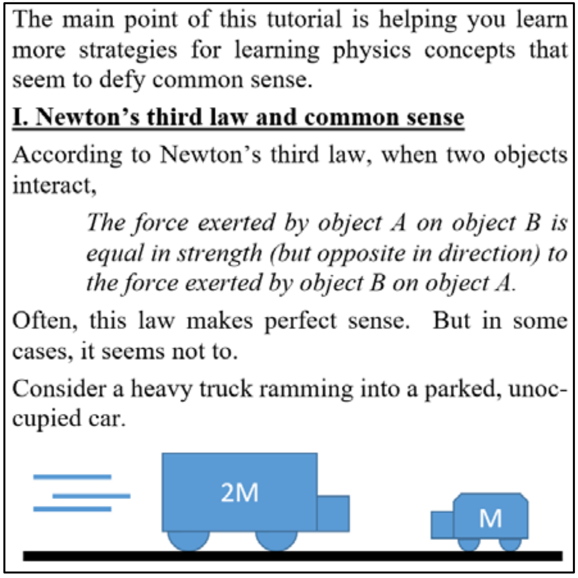
Created by the University of Maryland Physics Education Research Group, Open Source Tutorials (OSTs) are a collection of active-learning worksheets intended for use in the classroom. Although many OSTs are based upon Tutorials in Introductory Physics (TIPs) developed by the Physics Education Group at the University of Washington, some—like the tutorial on N3—are unique. TIPs are research-based in the sense that 1) the topics were chosen as a result of extensive physics education research on what topics are particularly difficult for students and 2) they have been developed through extensive testing, with many groups of students being observed in class to see how they interact with the lesson, and they have been shown to be substantially more effective than traditional instruction in helping students build a good conceptual understanding of physics (Tutorials from the UMD PERG, 2009).

OSTs and TIPs were developed to be given in a 50-minute class with approximately 15 to 30 students, divided into small groups of three to five students. The students are guided by the carefully designed worksheets (four to six pages), and each group generally works and reasons together, while instructor(s) rotate from group to group to facilitate the discussions and clarify any ambiguity in the instructions. These tutorials were created to be functional also in settings where computer tools are not available for each student, making modest use of digital resources. In order to promote authentic student discussions where students say what they really think (instead of giving the answers they think the teacher wants to hear), tutorials are usually not graded (often homework is assigned based upon the tutorial and sometimes exams incorporate tutorial-like questions so that students take tutorials seriously).

While both TIPs and OSTs aim to help students improve their conceptual understanding of tricky physics topics, OSTs place an additional explicit emphasis on epistemology. In particular, OSTs aim to have students come to value their intuitions in learning physics by seeing how their everyday experiences can be reconciled with the physics they learn (Tutorials from the UMD PERG, 2009). OSTs expect students to share and scrutinize their prior knowledge and intuitions and to consider the extent to which those intuitions agree with the concepts being studied. “Rather than just helping students resolve their difficulties, the OST[s] help students understand when their intuitive ideas are applicable and when not.” In terms of the “elicit, confront, resolve” process, OSTs explicitly have the “resolve” step be a process of refining existing (and misapplied) intuitions, which helps make epistemology more expert-like (Wittmann et al., 2009).

Although the developers specify that OSTs were designed so that each teacher can “make adjustments” in order to fit the worksheets to their individual instructional needs, teaching in OSTs in a manner faithful to their intended use is not trivial, in part due to the epistemological emphasis, which many teachers and students find off-putting (Tutorials from the UMD PERG, 2009). To help teachers avoid mistakes when administering the OSTs, the developers produced instructors manuals which call attention to some key guidelines behind the lessons. These manuals, together with the worksheets themselves (and the homework associated with each OST) are available for free for teachers online (Maryland Open Source Tutorials in Physics Sensemaking, 2011).

The Newton's Third Law Open Source Tutorial (N3 OST) (Open-source tutorials integrated with professional development materials, n.d.) considers students' intuitions about a collision of a heavy truck that rams into a parked car (see Figure 1, below). This is a situation in which all three facets of reasoning (action, mass, and velocity dependence) can be triggered.



The main point of this tutorial is helping you learn more strategies for learning physics concepts that seem to defy common sense.

I. Newton’s third law and common sense

According to Newton’s third law, when two objects interact,

> *The force exerted by object A on object B is equal in strength (but opposite in direction) to the force exerted by object B on object A.*

Often, this law makes perfect sense. But in some cases, it seems not to.

Consider a heavy truck ramming into a parked, unoccupied car.

Fig. 1: Excerpt from the Open Source Tutorial on Newton’s Third Law

Research has shown that the N3 OST helps students achieve a better conceptual understanding of N3, not only compared to traditional instruction, but compared to other active-learning worksheets. Smith and Wittmann (2007) have researched and compared three methods for teaching Newton's Third Law, including the OST and TIP, and concluded that students using the OST out-performed students using the other types of worksheets.

Our work involves the use of only the N3 OST in Austrian high schools, and our research question is:

- Can the Open Source Tutorial on Newton's Third Law help students in Austrian high schools achieve a better conceptual understanding as well as a better view about the nature of physics knowledge and learning (i.e. epistemology development), compared to their usual physics instruction?

As a "side question", we also investigated the extent to which learners accepted the teaching approach that was new to them:

- Will the N3 OST have a good acceptance among students, since it differs from what they are used to in traditional instruction?

3. Methodology

Our research priority was to compare the difference between traditional instruction with the intervention using OST on the same population of students, having the same parameters (conditions, background, culture, i.e., in Austria) and not the comparison with other samples of students of existing findings from other countries. Comparison between our findings with Austrian students and existing results and findings from other studies was secondary in importance.

At the time that our test instruments (described below) and the N3 OST were administered, students had already received traditional mechanics lessons from their teachers. Therefore, the pretest gave a good indication of students' status (in terms of N3 conceptual understanding and epistemology) after traditional instruction. Hence, we could say that the pretest for our study was simultaneously a post-test for the traditional instruction.

Between pre- and post-test there was a time elapse of approximately six weeks. During this period of time, the N3 OST was the only instruction about force or Newton's laws that students had, as their physics instruction did not discuss mechanics after the pretest.

Therefore, the post-test gave a good measure of students' status (in N3 conceptual understanding and their epistemology) after the OST intervention.

In order to have a wide sample of students from different courses and schools, i.e., a generalized and heterogeneous representation of Austrian high school students, we obtained data from a total of nine classes of students taken across three schools. Since not only the general high school (AHS – Allgemein bildende höhere Schule, including Gymnasium and Realgymnasium) but also the vocational school (BHS – Berufsbildende höhere Schule) accounts for a great percentage of youth's education in Austria (Bildung in Zahlen, 2020), we included both school types in the study (half of the students from AHS and half from BHS). In total, there were seven different course focuses represented: language, informatics, music, arts, sports, agriculture and agricultural machinery. This also enabled a good balance between gender (in some classes there were mainly girls, but in others mainly boys).

The decision as to which school year to involve in the study was made based on the official high schools' curricula (Lehrplan), provided by the Austrian Federal Ministry of Education, Science and Research (bmbwf) (Austrian Federal Ministry of Education, Science and Research, n.d.). Both the Lehrplan for AHS (Austrian official curriculum for general high schools, n.d.) and the Lehrplan for BHS (Austrian official curricula for vocational high schools, n.d.) prescribe the study of Newton's laws in the first year physics is learned in high school (which is not necessarily the first high school year; depending on school and course types, it can be either on the first, second or third high school year). As a result, the age range was quite large, ranging from 14 to 19 years old.

The total number of students, which took part in either the pretest, the OST, or the post-test (or in some combination of these) was 240. The analysis was made from the N = 181 students who participated in all three phases of the process.

The bulk of our research data comes from written surveys administered to students on the pretest and post-test sandwiching the N3 OST. To measure conceptual understanding about N3, we used items taken from the FCI. To consider epistemology, we had students answer these items in a "split task" format. We will discuss this test format after discussing the items on the conceptual survey themselves.

3.1. Force Test

The Force Concept Inventory (FCI) is a test instrument created by Hestenes, Wells and Swackhamer (1992) in the 1990s to evaluate student understanding of the fundamental concepts of Newtonian physics. Since its inception, the FCI has become the most internationally-used test for students' misconceptions in kinematics and dynamics, and it has established an extensive collection of test results.

The FCI is composed of 30 multiple-choice questions, each with five possible answers – from A to E. These items have been categorized into six major conceptual dimensions (Kinematics, First Law, Second Law, Third Law, Superposition Principle and Kinds of Force). There are no questions where calculations are necessary: the questions are purely conceptual. By answering the FCI multiple-choice questions, the student is compelled to make a decision between Newtonian concepts (represented by the one correct answer in each question) and commonsense alternatives – or misconceptions (represented by "distractors" distributed among the other four answer possibilities). At first glance, the FCI questions appear to be quite banal (and therefore not very revealing) to many physics teachers. These teachers are astonished when they find how badly their own students do on the test. Although there is controversy over individual items, the FCI as a whole is a good indicator of Newtonian thinking (Hestenes et al., 1992). Hestenes and Halloun (1995) stated that the FCI can be used for several different purposes, but that evaluating the effectiveness of instruction is the most appropriate one.

In order to measure the conceptual gains after N3 traditional instruction and after the N3 OST intervention, we created a survey containing the four FCI questions that relate to Newton's third law (FCI N3). However, a test containing only four difficult questions could lead to a floor effect, which is where measurement errors arise from an excess of low scores (i.e., we know the students did poorly, but we cannot adequately measure *****how* poorly they did). We also considered that a control measure would be important to compare students’ conceptual changes in other topics with those of N3. If students improved also in topics that were not discussed in the N3 OST, then there would be a good chance that the improvement on the N3 items was likewise due to some other factor beyond the N3 OST.

Taking these points into consideration, a “Force Test” with ten questions about forces was designed containing the following items:

a) four FCI N3 questions (for conceptual understanding about the content in the intervention);

b) three other FCI questions (as control measure);

c) three N3 “very easy" made up questions (to reduce floor effects).

The Force Test was administered using the “split task” format, which we will now discuss.

3.2. The Split Task Format

The “split task” format is a simple but rather amazing set of instructions that students follow in answering multiple choice items of a survey.

McCaskey and Elby (2005) explored the question: “Do students really believe the physical principles they learn in class?” by having students complete the FCI with the instructions that they should give two answers to each question. One answer (indicated with a circle) represented the answer which made “the most intuitive sense” to the student. The other (a square) represented the answer which the student thought “a scientist would give”. In this “split task” format, students are told clearly that they can (but do not need to) circle and square the same answer, if appropriate (McCaskey and Elby, 2005).

McCaskey and Elby showed in validation interviews of this methodology that “intuition splits" really do indicate a discrepancy between a student’s commonsense ideas and the answer he thinks a scientist would give. Furthermore, these interviews verified that focusing on the intuition split provides insight into the tendency and capacity students have to reconcile their intuitive ideas with physics concepts. The interviews showed the desire of some students to reconcile the squared and circled answers (McCaskey and Elby, 2005), exactly what OSTs aim to do.

3.3. Analysis Tools

In order to quantify the pre-post improvement made by students, we used the normalized gain (g) - or g-factor, which is often used by the physics education research community. The normalized gain is the number of points gained compared to the number of points that could have been gained; in other words, it is the ratio of the realized improvement to the maximum possible improvement. To check these gains for statistical significance, the p-value was calculated.

Furthermore, we used the t-test paired (two samples for means) with a significance level $\alpha = 0{,}05$ to determine if there is a significant difference between the arithmetic means of pre- and post-tests.

4. Analysis and Results

When analyzing the split task results, we differentiate between four possible outcomes:

a) “Right reconciled” means the correct answer was given for both the scientist's and the intuitive answer (not split).

b) “Right scientist” means the student selected the correct answer as the scientist's answer but a different answer for the intuitive one (split).

c) “Right intuition” is just the opposite of “right scientist”: the correct answer was given as the intuitive answer but a different answer was given as the scientist's one (split).

d) “Wrong” means both scientist's and intuitive answers were wrong, whether they agreed with each other or not.

We consider the “right scientist” splits to be the most important, as they show a lack of reconciliation between the student’s intuitions and what they (otherwise) successfully learned. However, we have also collapsed “right reconciled” and “right scientist” into one category (“right”) shown in the black bars in Figure 2 below. Similarly, we collapsed “right intuition” and “wrong” into the white bars (labeled “wrong”).

The calculation of the split percentage is the percentage of ``Right scientist" answers in relation to (divided by) the percentage of ``Right" answers.

The amount of right answers given on the four FCI N3 questions after traditional instruction was 31% and after the N3 OST was 62% (an increase of 1.24 points on average). The g-factor was $g = 0{,}45$ ($p = 6{,}71 \cdot 10^{-25} \ll \alpha$). The split percentage in the right answers was 41% (13/31) after traditional instruction and 29% (18/62) after the N3 OST intervention.

The amount of right answers given on the FCI N3 collision question after traditional instruction was 35% and after the N3 OST was 80% (an increase of 0.45 points). The g-factor was $g = 0{,}69$ ($p = 1{,}47 \cdot$

$10^{-19} \ll \alpha$). The split percentage in the right answers was 63% (22/35) after traditional instruction and 22% (18/80) after the N3 OST intervention.

The amount of right answers given on the non-N3 FCI items after traditional instruction was 30% and it remained at 30% after the N3 OST. The split percentage in the right answers was 29% (9/30) after traditional instruction and 27% (8/30) after the N3 OST intervention.

5. Discussion

Regarding conceptual learning gains about Newton's Third Law, the results from the four FCI N3 questions clearly reveal that students had a better understanding of N3 after the N3 OST than what they had learned with traditional instruction. The p-value being less than α indicates that there is a high probability that the collected data do not represent a random result, but rather that the OST is indeed more effective than traditional instruction.

Existing research has indicated that we can expect traditional physics instruction to yield a normalized gain as small as g ~ 0,2. Physics courses that are research-based and that utilize interactive engagement obtain higher normalized gains, ranging from g ~ 0,35 to g ~ 0,6, depending on the extent of the reform (Redish and Hammer, 2009). The result of g ~ 0,45 on the four N3 FCI items achieved in Austrian high schools for one 50-minute intervention with the N3 OST was within this range.

Although the FCI was not designed to have conclusions drawn on the basis of individual items, we decided to look specifically at the one FCI N3 collision question, since the N3 OST focuses exclusively upon such a collision situation. The number of students who answered this question correctly after the N3 OST intervention was dramatically more than after traditional instruction. On the pretest, 64 out of N = 181 students answered this question correctly but on the post-test, this number escalated to 145 (2,27 times more). We can also see a dramatic difference in comparing the normalized gain of the arithmetic means (g) from the group "FCI N3 questions" (0,45), which includes three pushing items and the one collision item, with the g from that one FCI N3 collision question (0,69). It is clear that there are a number of students who do not transfer what they learned in the N3 OST about collisions to reasoning about pushing. This supports the decision of Smith and Wittmann (2007) to distinguish pushing situations from collision situations: for at least some students in Austria, they are different contexts which trigger different reasoning patterns.

The null result from the non-N3 FCI items has important conclusions as well. Since the N3 OST does not discuss the force topics discussed in these items, we did not expect a gain on these items. To be more precise, we had *hoped* to not see a gain with these items, as such a gain would indicate that the student had had some exposure to mechanics instruction other than the N3 OST in between pretest and post-test. Were that the case, then we would not be able to claim that gains on the N3 FCI items were due to the N3 OST (they may have been due to that additional instruction instead). This lack of improvement on the non-N3 FCI items, together with the growth on the N3 items, suggests that the growth on the N3 items did indeed come from the N3 OST.

In terms of epistemology, the split task results clearly indicates an epistemological growth from the pretest to the post-test. Not only a bigger percentage of the students knew the correct scientific answer to the FCI N3 questions (larger black bars), but also a higher percentage of those students indicated that the correct answers made intuitive sense. From the students who answered the right answers on the FCI N3 after traditional instruction 41% had splits, and after the N3 OST instruction this number was reduced to 28%. Particularly impressive is the dramatic change that can be seen in the collision question, where these numbers are 63% versus 22%. Lower split rates indicate that students have reconciled Newton's Third Law with their intuitive ideas. In this sense, after traditional instruction, even students who had "learned" N3 had not done so as "deeply" as they did after the N3 OST intervention.

6. Conclusions and Further Work

As a result of a single 50-minute lesson using the Open Source Tutorial on Newton's Third Law, students increased their conceptual understanding of N3, as indicated by the four N3 FCI items administered pre- and post-intervention. More than that, this new knowledge actually made sense for them. Many of the students had reconciled their intuitive ideas with the correct scientific concepts. This shows that the OST's "epistemological plan" to help students understand both science and learning as "a refinement of everyday thinking" can be effective also with Austrian high school students.

The learning indicated by the Force Test is consistent with observations made by the first author in the classroom as she carried out the OST. According to her field notes, students worked well together during the OST, showing excitement and enjoyment. They worked actively, had discussions that were intent and on-topic, and even expressed disappointment when they realized that they would not experience the OST style of learning beyond the one lesson. Many students gave additional positive feedback as well, for example, that the OST had helped them on the post-test.

Based upon our findings, we advise that teachers consider incorporating the N3 OST into their mechanics lessons and that further research attend to assessing the effectiveness of other OSTs in Austrian high

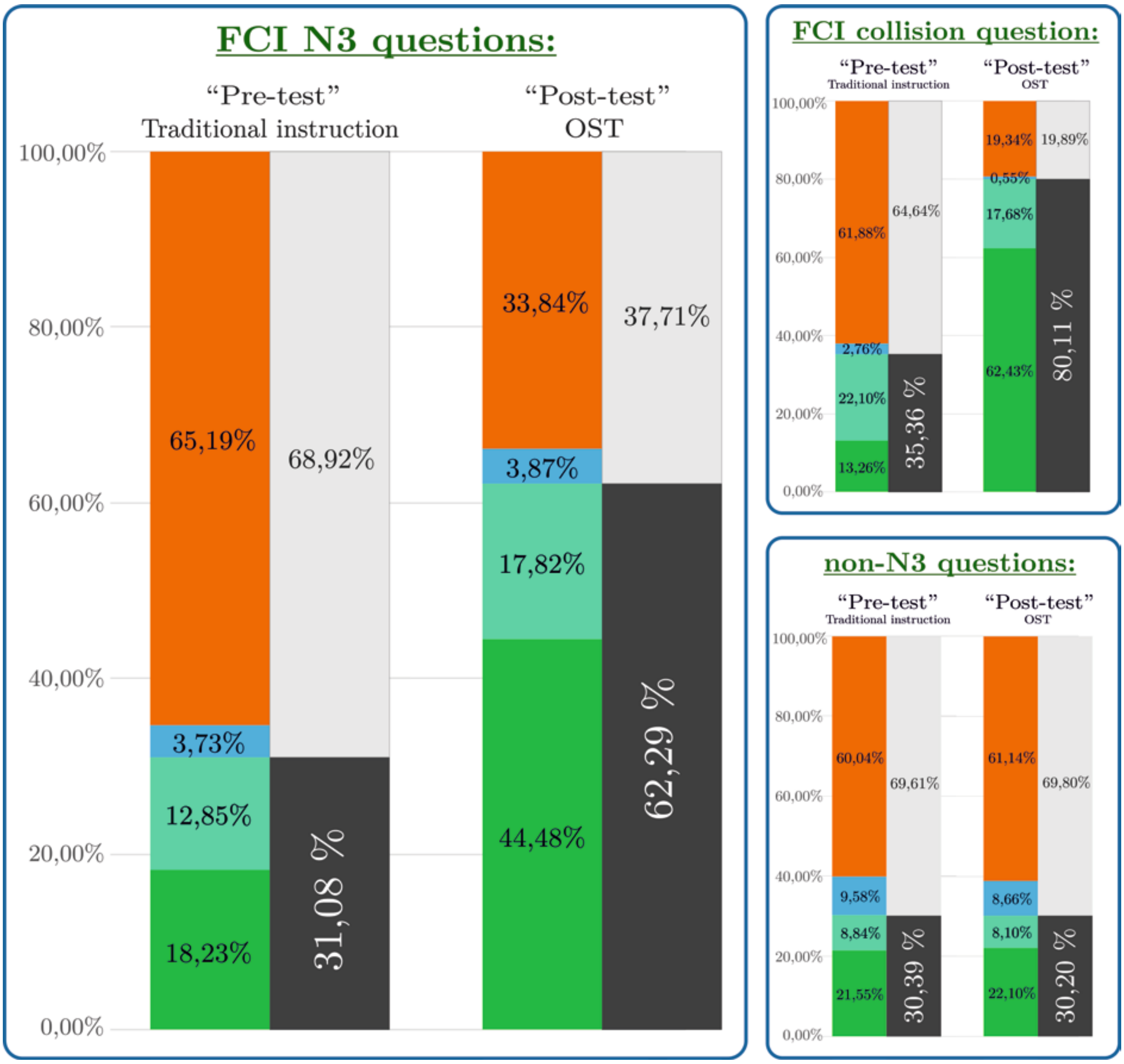


Fig. 2: Results from the four N3 FCI items (left), the item of those four specific to the case of a collision (top-right), and the non-N3 FCI items (bottom-right). The three "very easy" items ended up not being necessary to avoid the floor effect and are not in the graphs. Black bars indicate correct responses, comprised of "right reconciled" (dark green) and "right scientist" (light green). White bars indicate incorrect responses, comprised of "right intuition" (blue) and "wrong" (orange).

schools. We think it would be productive also to expand the N3 OST to include also pushing and pulling situations to help students understand N3 even better.

Although a German translation of the Maryland Physics Expectations (MPEX) Survey exists, additional work is needed to validate the survey. Such an instrument would enable surveying student views about the nature of physics knowledge and learning more directly than with the split task format. The first author found in her MS thesis that student epistemology, as measured by the current version of the German MPEX, did not improve pretest to post-test. This is consistent with Elby's warning that "isolated pieces of epistemologically focused curriculum aren't enough" (Elby, 2001). It may be the case that this would be the case even with a finalized German translation of the MPEX. Further work should investigate the effects of using OSTs throughout the school year on high school student epistemological development.

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