Teaching middle school physics in Observer-dependence approach: pedagogical and curricular aspects

Ben STEIN, Hana STEIN, Igal GALILI
Science Education, The Hebrew University of Jerusalem, Israel

Abstract. Physics curriculum of middle school and high school is based on the classic perspective of the 19th century and avoids dealing with the concept of observer (frame of reference). This by far holds regarding the curriculum of middle school, as even though it includes numerous observer-dependent concepts (location, trajectory, displacement, velocity, force, energy, work), it entirely excludes observer and observer dependent description of reality, and they are not taught as such.

This tradition apparently draws on the assumption that students are incapable of learning observer dependent concepts because that requires an account with multiple answers valid for different observers. For that reason it is considered to be as a sort of advanced subject matter that should be treated at higher education level.

We empirically checked this convention and discovered that 9th grade students succeeded in applying frame of reference dependence to their accounts of daily experiences. For example, they were able to construct graphs expressing dependence of displacement, distance, and velocity on time in the perspective of different inertial frames of references. The results clearly indicate that integrated observer-dependent concepts in middle school promises substantial educational and pedagogical benefits (e.g. wider space of learning, intuitively and meaningful learning, students' engagement and adequate image of science).

1. Theoretical Background
The concept of observer is one of the most fundamental in physics. It was present in the scientific discourse for many years and it plays a central role in the paradigmatic change that has taken place from the physics of 17-19th centuries to the physics of our days. Such topics as Galileo's principle of relativity, equivalence principle, inertial forces, and concept definitions - all involve observer dependence as essential aspect.

Despite of its importance, the physics curriculum of Israeli schools (and commonly in its parallels in other countries) is based on the classic perspective of the 19th century and avoids dealing with modern epistemology ascribing important role to the concept of observer (Galili and Kaplan, 1997).

This by far holds regarding the curriculum of middle school, as even though it includes numerous observer-dependent concepts (location, trajectory, displacement, velocity, force, energy, work), it entirely excludes observer and observer dependent description of reality. Even the inherently relative concepts are not taught as such.

One of the main reasons for ignoring the concept of observer might be considering it as an advanced subject matter to be treated at higher education level. This consideration seemingly draws on the assumption that middle school students are premature for learning observer-based concepts as those require multi-perspectivist account.
In contrast to the assumption that learning observer-dependent concepts is more difficult than observer independent ones, there are pedagogical arguments that can indicate the opposite. They point to the fact that teaching concepts as observer-dependent often match students' naïve knowledge (pre-instructional perceptions) originated from daily experience and related to their "body knowledge". Galili and Kaplan (1996) related this aspect with regard to the employment of operational definitions of physical concepts (particularly with respect to the concept of weight).

The present study investigated these cognitive and pedagogical claims of curricular limitations. It empirically examined the feasibility of alternative teaching and the implications of integrating the concept of observer as early as in middle school science, and analyzed students' pertinent abilities.

2. Research questions
The stated goals of this study implied the following cluster of research questions:

a) What is the feasibility that middle school students are capable to learn observer-dependent concepts and handle their application?

b) Whether and to what extent there is a pedagogical and content knowledge efficiency of observer-dependence integrated teaching in comparison to the traditional teaching?

c) What are the characteristics of students' naïve knowledge with regard to observer dependent concepts? Whether and to what extent there is a (statistical) relationship between students' naive knowledge and their success in learning this domain of physics knowledge?

d) What is the impact of observer-dependence integrated teaching on students' engagement in physics lessons (attitude towards physics, interest and learning experience)?

3. Methodology

3.1. Participants and settings
The study lasted three years and was comprised of two stages. The pilot stage included a yearlong instruction of 8th grade students (N=16). It provided the initial information with regard to the ability of middle school students to learn observer-dependent concepts and handle their application. After the initial evidence of feasibility, the research proceeded to the major (second) stage that lasted two years and included 9th grade students (N=117). This stage involved research and control groups, which provided the answers to all of the research questions.

The new teaching materials and teaching deployment were developed for the innovative teaching. They included the curriculum content for middle school classes with advanced reference to observer-dependent concepts. The pilot stage included 15 lessons addressing selected topics of kinematics (velocity, acceleration, trajectory) and dynamics (forces, weight and gravitation, energy and work) while introducing their observer dependence. The second stage included 12 lessons, which dealt with a slightly shorter list of the same concepts. The teaching in the control groups was in accordance with the regular curriculum (without innovations).

3.2. Data Collection and Analysis Tools
The data was collected via four open-ended questionnaires (Pre-test, two Post-tests and anonymous questionnaire) and was analyzed both qualitatively and quantitatively:

Pre-test (mapping naïve knowledge) administered to the participants prior to learning in order to elicit students' naïve knowledge regarding observer-dependent concepts. It included 14 questions, which addressed various situations (examples in figure 1). The students' verbal answers were qualitatively analyzed in accordance to seven characteristics (e.g. Students' preference for using internal or external observer; students' consideration regarding the validity of different observers; capability to account situations by different observers etc.). In order to insure equality between research and control groups before learning, Levene's test for equality of variance and t-test for independent samples were applied separately on both students' mathematics grades (which were taken as an indicator of their learning abilities) and their Pre-test results.

The First Post-test was applied on the experimental teaching group after instruction in both stages of the study. It included 14 questions for evaluating students' conceptual knowledge and skills
regarding the observer-dependence. The test of each student was examined separately for each of the subjects of knowledge learned in relation to the observer concept: Kinematic (4 ques.); Forces (4 ques.); Weight and Gravitation (6 ques.). The analysis of the students' verbal answers was based on several categories related to students' abilities with regard to the concept of observer, e.g. diagrammatic descriptions of forces in different frames of references, construction of appropriate equations, choosing an effective frame of reference etc. All the abilities examined are detailed in Table 1.

Statistical analysis informed about the relationship (significance and correlation) between Pre-test (naive knowledge) and First Post-test (success in learning observer-dependent concepts). An additional statistical analysis of multiple linear regression was performed to distinguish between the contribution of students' naive knowledge and the contribution of their learning capabilities (indicated by their mathematics' grades) to their success in learning observer-dependent concepts.

The Second Post-test was given to both research and control groups in the second stage of the study. It compared their knowledge and skills with respect to subject matter from the traditional curriculum requirements and did not mention any observer. The test included 17 questions: Kinematic (7 ques.); Forces (5 ques.); Weight and Gravitation (5 ques.). Yet, in order to examine the difference between the two groups we deliberately wrote two types of questions. The first - possessed a more familiar to the students content (e.g. comparison between two masses dropped from the same height), while the second type of questions were more challenging, requiring deeper thinking (e.g. Does the Moon weigh more/less/the same as the Earth?). A t-test for independent samples was applied to establish the statistical significance of the difference between experimental and control groups in the Second Post-test results at both types of questions.

The additional anonymous questionnaire evaluated the affective impact of the experimental teaching: students' satisfaction with classroom experience, their attitude towards physics learning, interest and engagement.

Figure 1. Some of the situations that were presented to the students in the Pre-test, in which the students were asked to choose the path of a body, as seen by an external observer.

4. Findings and their Analysis
The data analysis provided rich information in the dimensions of interest. It facilitated quantitative and qualitative analysis for cognitive and pedagogical claims related to teaching and learning observer-dependent concepts at middle school. The results clearly illustrated the positive impact of integrating the concept of observer in middle school science teaching. The main findings included the following:

a) It was found that 9th grade students succeeded in understanding observer-dependent concepts as indicated in their successful application of them in accounting of physical situations. This result holds with regard to kinematic and dynamic concepts. Students were able to produce graphical account of displacement, distance, and velocity as a function of time in different frames of references; to draw force diagrams with respect to inertial and non-inertial frames of references; to use complementary definitions of the concept of weight, theoretical and operational. The First Post-test average score in experimental group was 80 in kinematics, 76 regarding forces and 81 regarding weight,
weightlessness and gravitation. Figures 2-6 introduce representative answers of the first post-test. Table 1 displays the results of the first post-test categorized by subjects and abilities.

**Figure 2.** (a) the graphs of velocity and displacement versus time of the girl walking back and forth at different speeds with respect to three observers (in the house, next to the tree -10 meters aside, the boy walking at 2 m/sec to the right); (b) determining the distance and displacement of this girl with respect to the same kind of observers (the house, the tree and the boy).

**Figure 3.** Computation of the time required for two travelers on a ship to meet in view of three observers. The answer includes three different equations with the same result – 33.5 sec (highlighted).
Table 1. Post-test results in terms of subjects and abilities.

| Subject                      | Abilities that were examined with regard to the concept of observer                                                                 | Average grade (0-100) | Standard deviation |
|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|-----------------------|--------------------|
| **Kinematic**                | Production of graphical dependence of displacement, distance, and velocity as a function of time in different frames of references    | 86                    | 25                 |
|                              | Calculation displacement and distance in reference to three different inertial observers                                          | 76                    | 31                 |
|                              | Creating algebraic equations of kinematic problems in reference to three different inertial observers (Computation of the time required to two travelers to meet) | 83                    | 30                 |
|                              | Understanding the equivalence of solutions in different frames of reference (variant and invariant concepts)                     | 79                    | 35                 |
|                              | Ability to choose the most effective frame of reference in solving a kinematic problem                                          | 78                    | 32                 |
|                              | Ability to mediate between the graphs produced in reference to different observers                                               | 69                    | 24                 |
|                              | Describing trajectory of moving body as viewed by different observers                                                                 | 92                    | 18                 |
| **Kinematic post-test grade (weighted average)** |                                                                                                                                  | 80                    | 18                 |
| **Forces in different perspectives** | Using Newton's second law of motion in order to explain why force might be observer dependent                                      | 58                    | 38                 |
|                              | Giving examples of how force is inferred by different observers                                                                      | 64                    | 41                 |
|                              | Understanding the difference between theoretical and operational approach to force definition                                     | 86                    | 23                 |
|                              | Analyzing motion in reference to a non-inertial observer (force diagram from the point of view of the observer on a rotating platform). Inertial force. | 81                    | 33                 |
|                              | Analyzing circular motion in reference to an inertial observer (force diagram of a rotating body from the point of view of the external observer) | 77                    | 34                 |
|                              | Explanation and implementation of Galileo's principle of relativity                                                                     | 95                    |                    |
|                              | The account of accelerating body (linear motion) in reference to a non-inertial observer                                               | 83                    |                    |
|                              | The account of accelerating body (linear movement) in reference to an inert observer                                                   | 79                    |                    |
| **Force account post-test grade (weighted average)** |                                                                                                                                  | 76                    | 20                 |
| **Weight, weightlessness and Gravitation** | Explaining the concepts of weight and gravitation (operational and gravitational definitions)                                      | 73                    | 23                 |
|                              | Explaining Newton's cannonball thought experiment                                                                                   | 79                    | 28                 |
|                              | Explaining weightlessness of an astronaut inside an orbiting satellite from the point of view of inertial observer (at rest relating to the Sun) | 63                    | 40                 |
|                              | Force diagram for an astronaut orbiting the Earth and of a man in a free-falling elevator in reference to the observer at rest on the ground | 73.5                  |                    |
|                              | Explaining weightlessness of an astronaut in a satellite from the point of view inside the cabin                                    | 85                    | 30                 |
|                              | Force diagram of an astronaut orbiting earth and of a person in a falling elevator in reference to a non-inertial observer         | 80.5                  |                    |
|                              | Understanding up - down as operationally defined relative concepts                                                                      | 89                    | 21                 |
| **Weight and Gravitation post-test grade (weighted average)** |                                                                                                                                  | 81                    | 15                 |
Dany was travelling in a train. As the train approached the station, the driver pressed the brakes, and Dany fell forward.

Try to explain why?

Student answer:  

a) The observer that looks on the train from outside will notice that the train is changing its velocity, while the passenger proceeds in motion due to his velocity. This observer from outside does not infer about any force on the passenger (see the right diagram).

b) The observer that examines the passenger from the inside of the train will say that the passenger was standing still and suddenly started to fall forward. That implies the change of his motion. Therefore, this observer will conclude that a force was involved – the imaginary force $F_i$ (see the left diagram).

Draw a suitable force diagram

---

**Figure 4.** Explanation of a passenger falling forward at a stopping train. The student provides explanations on behalf of two different observers.

With regard to the upper diagram, a student wrote:  

The observer from inside can't see that the astronaut is continuously changing his direction of motion and therefore the observer will conclude that the net force on the astronauts is zero. Knowing about the gravitational force attracting the astronaut the observer will infer regarding the force in the opposite direction to the gravitation that nullifies it.

With regard to the bottom diagram, the student wrote:  

In the eyes of the observer who is watching the astronaut from the outside – the astronaut is constantly changing his direction towards the Earth and therefore the net force on him is not zero.

**Figure 5.** Drawing a force diagram for an astronaut orbiting the Earth in reference to two observers.

**Figure 6.** Drawing the force diagram for a ball in circular motion in reference to two observers.
b) Through using observer-dependent concepts, the students showed greater affinity to modern physics in their manipulating with frames of reference, including non-inertial ones, using inertial forces (surpassing the regular curriculum) and operational concept definitions in daily context, showing better intuition and "body knowledge". There was a significant positive correlation (r=0.57, p=0.00) between students' naive knowledge and students' success in learning observer-dependent concepts (graph 1). The multiple linear regression analysis (Table 2) showed that students' naive knowledge (regardless learning capabilities) significantly contribute to learning success (β=0.461, p=0.000). This contribution was greater than the contribution of learning capabilities (β=0.379, p=0.001).

c) The observer-dependence integration significantly helped students in achieving mature conceptual knowledge of classical mechanics. It provided students with better tools for dealing with the content as manifested in the significantly higher score of those who learned observer dependence: 13 points in the questions of familiar type (t(115)=4.129, p=0.000) and 28 points in the unfamiliar questions (t(115)=6.115, p=0.000). Histograms (Graphs 2-4) shows that the research group accumulated higher scores than the control group. This observation was true not just by averages grades, but almost in each and every question of the test. Table 3 displays the grade differences between the groups segmented to two criteria: (a) ordinary familiar questions; (b) challenging creative questions, and the results of their corresponding statistical analysis.
As can see from table 3, the difference between the groups was statistically significant (p<0.05) in all cases except the ordinary familiar questions in the forces account. Graph 5 shows the compound influence between the question kind (familiar/challenging) and the group type. The statistical analysis of the average grades shows that:

(i) The research group grades are significantly higher than those of the control group (F(1)=419.09, p=0.00).

(ii) Students were significantly more successful in familiar questions than in unfamiliar ones (F(1)=35.02, p=0.00).

(iii) A significant compound influence was found between the question type (familiar/challenging) and the group type, so that the difference in average scores between the control group and the research group was significantly greater in challenging questions than in familiar ones (F(1)=16.235, p=0.00).
Beyond the numerical and statistical outcomes, the research group stood out in some prominent characteristics to be mentioned:

(i) The experimental teaching group answers were more scientifically accurate as the students referred in their account for the situation by mentioning the frame of reference used;
(ii) The experimental teaching group used richer vocabulary and the students were more precise in using definitions;
(iii) A considerable proportion of the experimental teaching group regularly introduced more than one solution to each problem. For example, one of the research group students used two explanations addressing the simultaneous falling of heavy and light bodies. The student wrote: (1) "both bodies have the same velocity because the earth attracts the heavy body (greater mass) with greater force and therefore the acceleration is the same as the formula F=ma implies", (2) using the operational definition of weight he wrote: "as they are free falling - both bodies weight zero, and therefore it is reasonable that they will fall at the same time."

Another worth to mention finding was that in questions that contained moving platform (passengers in a moving train or ship) a substantial portion of 30% to 62% of the control group solved the problem with respect to the moving platform, even if it was accelerating (in odds with the traditional curriculum). This finding reapproved Galili and Kaplan (2002) claim that even good students fail in keeping with the requirement to dismiss inertial force ("internal driving force") and use force account only within the point of view of an inertial observer.

e) Integrating the observer dependence of concepts in middle school science had a positive impact on students' engagement, interest and learning experience as registered at personal level (relating physics to daily experiences) as well as class level (engagement in discussions). in particular:

(i) 92% of the students mentioned the innovative learning as very interesting; 83% expressed satisfaction with learning to solve kinematic problems with respect to different frames of reference, and claimed that the ability to choose frame of reference facilitated their solution (89%).
(ii) 82% of the students indicated that solving the same problem with respect to different observers greatly reinforced their understanding of the subject matter.

(iii) Most of the students (75%) indicated that the learning process and integration of observer-dependence strengthened the relevance of learning Physics to their everyday life.

(iv) 81% indicated that they would like to learn more with this "experimental teaching", 95% stated that Physics is a very interesting subject matter, and 76% wrote that they would choose to study Physics even if it was not mandatory.

5. Implications for teaching
The study results suggest that the considered curricular change promises substantial educational benefits in several aspects.

Firstly, it restores the true observer-dependent nature to the numerous concepts of middle school physics, which are not taught as such. Learning in Observer dependence approach will removes this deficiency.

Secondly, the new teaching stimulates students to employ nominal and operational definitions regarding each physics concept, and thus, providing the learner with meaningful knowledge. For example, upgrading the concept of force by operational definition and legitimization of inertial force reveals to school students the difference between the classical and modern paradigms of mechanics. This gain can treat the known misconceptions of force-motion relationship and weight-gravitation.

Thirdly, the study supports teaching by "refinement" of intuitive knowledge instead of its replacement (Grayson, 2004). The applied teaching approach legitimizes some naïve interpretations of tactile perception and converts them to scaffolding on the way to the scientific knowledge (such as when matching sense perception with operational definition in accelerated frames of reference). This is in contrast to the existing view considering students' intuition merely as a misleading factor.

Fourthly, the results suggest application of constructivist pedagogy in physics class and reliance on the novel paradigm of the Discipline-Culture (Tseitlin and Galili, 2005). The latter suggests revealing to the learners the dialogue between classical and modern physics with regard to the observer dependent concepts.

6. Concluding remarks
Teaching mechanics at schools practically ignores the great knowledge revolutions of the 20th century. The results of this study show that introduction of observer-dependent concepts already in middle school curriculum is feasible and can serve as a powerful tool that establishes a wider space of learning, promotes meaningful knowledge of physics concepts and expands their validity area. These gains cause more mature and genuine knowledge of classical mechanics and create an adequate image of science among middle school students. This curricular change in physics teaching closes the gap between school physics and its contemporary content.

7. References
[1] Galili I and Kaplan D 1996 Students operation with the concept of weight. Sci. Edu. 80 (4) pp 457-487
[2] Galili I and Kaplan D 1997 Extending the use of the relativity principle: some pedagogical advantages, American Journal of Phys. 65 (1) pp 328-335
[3] Galili I and Kaplan D 2002 Students interpretation of water surface orientation and inertial forces in physics curriculum. Praxis der Naturwissenschaften Phys. in der Schule, 51(7) pp 2-11
[4] Grayson D 2004 Concept substitution: A teaching strategy for helping students disentangle related physics concepts. American Journal of Phys. 72(8) pp 1126-1133
[5] Tseitlin M and Galili I 2005 Physics teaching in the search for its self: from a physics-discipline to a physics-culture. Sci. and Edu. 14 (3-5) pp 235-261