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# The Concept of Observer in Science Teaching in Middle School: Pre-Instructional Knowledge as a Lever for Learning rather than an Obstacle

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**Abstract:** This study deals with the concept of the *observer* in science education, which is currently significantly diminished at school. In the first part, we review the theoretical perspective of the concept, regarding its historical role in physics knowledge, cognitive aspects of learning and the relevant curricular situation. The second part of the study was devoted to the experiment, which included constructing new materials to facilitate interpretation of physical situations by inertial and non-inertial observers in teaching students in middle schools. The impact of the experimental teaching was assessed by an open questionnaire addressing content knowledge and affective perception of the new material. The significant positive results obtained testify to the feasibility of such innovative teaching. It has a strong advantage in comparison with the regular teaching in the control group. The implication of the study could be significant changes which would upgrade school physics curricula. The explicit inclusion of the inertial forces—instead of banning them, as currently practised—maturates the physics knowledge of school students while resonating with their naive views on the subject.

**Keywords:** the concept of observer in mechanics; observer dependent concepts in middle school; teaching inertial forces; pre-instructional knowledge

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**Citation:** Stein, B.; Stein, H.; Galili, I. The Concept of Observer in Science Teaching in Middle School: Pre-Instructional Knowledge as a Lever for Learning rather than an Obstacle. *Educ. Sci.* **2023**, *13*, 95. https://doi.org/10.3390/educsci13010095

Academic Editor: James Albright

Received: 27 November 2022
Revised: 25 December 2022
Accepted: 30 December 2022
Published: 16 January 2023



## 1. Introduction

This study deals with the concept of the *observer* in science education. This concept is among the central and most fundamental concepts of physics: space, distance, time, forces, etc. This is the case in science, while in other domains of social reality, *observer* possesses a different meaning: that of a person who observes as opposed to one who participates, reflects, interprets, analyses in accordance with his/her knowledge, worldview and conceptions. That is to say, outside the context of science, the observer incorporates subjective and objective aspects of activity. The observer in science, however, essentially presumes measurement, the performance of which is independent of the personality of the observer even though it is inevitably interwoven with a theoretical interpretation of meaning. The tradition of collecting and manipulating empirical data is as old as science itself. "Count, weigh, measure" was stated by King Solomon in The Book of Wisdom (11.21) guiding an empirical investigation by an observer seeking the truth about the world. In our day, by the term *observer* in science, we presume a whole laboratory of apparatus performing measurements.

In modern physics, the concept of observer is central in three fundamental theories—quantum theory, special and general relativity. In quantum theory, the observer—the kind of apparatus used in measurement—determines the aspect of reality in the duality of particle features. In relativity, the choice of observer, the chosen frame of reference in which the measurement is performed, reveals such features of objects as the velocity, displacement and time interval in kinematics, energy (work) and momentum in dynamics. Special relativity is valid for inertial observers, and general relativity expands its validity to any observer. The inclusion of the accelerated frames of reference involves the principle of equivalence, which equates the nature of inertial forces appearing in such frames with the gravitation. The validity of an accelerated observer and his theoretical account of reality is reached through using inertial forces.

Modern physics is only the background to this study, providing a special motivation to addressing the *observer* concept in school education, which is solely in classical mechanics. In particular, we consider the concept of the observer in its important dynamic aspect, which is its closeness to students' intuition, which can change the consideration regarding its adoption to the curriculum. To consider this subject, we firstly review it in science and education, which we do in the theoretical part of this article. In the second part, we describe the empirical effort to teach observer dependence of the physical account in school mechanics. We present the teaching experiment with regular middle school students and analyze the obtained results.

## 2. Theoretical Background

### *2.1. Cognitive Difficulties in Learning Science*

Various theories discuss the complexity of teaching-learning processes explaining how people learn, what is the role of their naive knowledge, and what is meaningful learning and teaching. Early theories such as behaviorism (stimulus—response model) did not analyze the underpinning cognition that determined the learning result, considering it in terms of right and wrong in acquisition and application. Accordingly, the assessment focused on the ability to follow rules, to master the algorithmic skills of solving standard problems preferably on a continuous scale of abilities rather than "good" and "bad" dichotomy. Within this vision, researchers refined the cognitive skills required by the learners of science [1].

However, dissatisfaction with the inability to control the learning process and lacking effective guidance via a vis learning caused increased interest beyond detailed instruction and correction of errors. Researchers identified the systematic mistakes as representing students' conceptions and made them as the focus of their investigation. They considered and revealed the mental processes by which the learner adopted scientific knowledge, the individual reconstruction using the already possessed knowledge. The new constructivist theory of learning stated that learning is more than a replacement or accretion but rather a complex structural adaptive transformation of knowledge in its growth.

In any act of learning, the already possessed knowledge in the form of pre-conceptions and intuition interacts with the new knowledge of the subject. In this process of adaptation, the new knowledge is assimilated while changing its form in its interpretation and performing cognitive accommodation (Piaget's model of cognitive adaptation in e.g., [2] (pp. 13–25), [3] (pp. 5–10)). Students' knowledge can be represented in the form of schemes, explanatory patterns (Piaget's schemata), which are the logical conceptual constructs drawing on personal intuitive experience or the pieces manifested in social interaction [4–6]. It appears possible to identify facets-of-knowledge [7] or p-prims (phenomenological primitives) [8], p-prim is not a refining of facets but a different construct and to organize them in a scheme-facets hierarchical structure representing knowledge in a certain domain of reality [9]. One may compare such conceptual development in learning with the introduction of new concepts in science where it also draws on the previous knowledge [10]. Considering the revealed similarity, researchers formulated the necessary conditions of individual learning which in a way recapitulated conceptual development in science [11].

Education studies revealed that the intuitive perception of the world is closer to historically early theories of physics, rather than to Newton's mechanics. This fits in with the general idea of recapitulation, that is to say, the individual development shows features of the historical progression of collective knowledge [12], thus implying the important role of intuitive knowledge. Intuitive conceptions of students are often consistent with

Aristotelian or medieval physics [13–18]. In the student's mind, they coexist with scientific concepts but are retrieved as alternative explanations, especially when considering novel and non-obvious physical situations [19], including by adults [20]. Research evidence calls for dealing with intuitive conceptions in considering the learning process. Intuitive theories manifest themselves in spoken language, explanations of natural phenomena and everyday situations, such as the motion of sun and stars, "active vision" (or vision rays), heat as a property ("warm clothes", "cold wind") and many others [21]. Facing this reality, researchers suggested considering *representative sets* of physical situations for each specific concept taught in order to facilitate construction of valid scientific concepts [22–24].

The conceptual account of the *force* concept and the force-motion relationship are among those frequently considered in education for being salient in everyday experience. For example, contrary to the Newtonian view, students often believe that motion implies force. In other words, an object moving indicates a force pushing it to maintain motion, regardless the kind of motion. The required conceptual change presumes a special teaching, which refines rather than replaces this naïve knowledge [25,26]. Thus, the highly intuitive concept of impetus could be transformed to the correct concept of momentum. Instead of considering intuition as a barrier, it could be used productively, as a lever for conceptual modification. Here, we argue with regard to the force concept involving another concept of fundamental importance: The concept of the observer.

### 2.2. The Concept of Observer in Physics

The concept of observer is among the most fundamental concepts in physics. It is extremely rich philosophically, both from ontological and epistemological perspectives. Historically, an observer-philosopher was presumed in Aristotelian physics as the agent who revealed causality in the real world through his contemplation, using a specific inductive-deductive method [27]. In mediaeval physics, it was recognized by the leading scholars (Buridan, Oresme, Nicolas of Cusa) specifically in the perception of motion being relative and observer dependent [28]. A more advanced approach was shown by Bruno, who, while using the metaphor of a coasting ship (moving uniformly) dismissed the empirical evidence of the motion in the reality observed in a closed cabin [29]. This vision became known to all after its elaboration by Galileo, who depicted this reality as absolutely indifferent to motion [30] (pp. 186–187). This description declared itself, still outside any fundamental theory, as the Galileo principle of relativity, and has been since then identified as a cornerstone of classical physics. Galileo's vision facilitated and heralded the coming physical theory of classical mechanics.

The next significant advancement, later in the 17th century, was the actual application of the relativity principle by Huygens in his account of collisions between hard bodies [31] (pp. 313–317). In this way he discovered the conservation of the quantity, *vis viva* ($mv^2$) or, later, kinetic energy ($mv^2/2$). Yet, the apex of his progress was the idea of a different kind of observer, the *non-inertial* one (as we term him now), the observer on a rotating disc. For the first time, while considering the experience of this observer, Huygens introduced the centrifugal force, *vis centrifuga*, as a natural concept for the observer [32], while that force remained unjustified for the outside inertial observer.

For a long time, this progress of Huygens was not appropriately appreciated in classical physics and remained in the shadows, actually until Einstein, at the beginning of the 20th century [33,34]. Einstein introduced a new account of reality equally valid for all inertial observers: The special theory of relativity. The emerged multitude of observers replaced the Newtonian worldview: The unique picture of the universe perceived by the observer at rest in absolute space and time.

The observer-dependence of the kinematic concepts describing the motion of objects in a relative manner—location, displacement, velocity—was accepted from medieval times. However, with regard to dynamics, the picture became more complex. In classical mechanics, observer-dependence incorporates kinetic and potential energies, work, momentum [35–38]. Regarding the concept of force, Newtonian mechanics, valid in the inertial frames of reference (inertial observers), employed only interactive forces (subdued to Newton's third law). Inertial forces destroyed this harmony, being non-interactive and observer dependent, missing for an inertial observer. Within the Newtonian vision of the unique absolute observer, they were considered "fictitious", "pseudo-forces", "imaginary" (in contrast to the "real"), not really "existing". Observing this incompatibility of Huygens' view with his theory, Newton reacted by redefining the new force, adjusting it to his framework. In contrast with Huygens, Newton named as the *centrifugal* force the counterpart of the *centripetal* force, thus making them an interactive pair [33,39].

By expanding the validity of mechanics to the non-inertial observers, Einstein legitimized inertial forces in Huygens' sense, as being real, and as real as the interactive forces, both mental tools [40,41]. The new vision implied descriptions by any observer in relative motion. In the new theory, all such descriptions were related by the rules of transformation within a unified world picture. It was the principle of equivalence between gravitation and inertial forces that furnished the inclusion of any observer (frame of reference) and made the principle of relativity really truly universal. Interactive and non-interactive (inertial) forces became equally valid.

The next upgrading of the observer concept was within quantum theory, valid at the atomic scale. The observer chooses the experimental setting, but so he does in classical physics. The specific feature of the new theory was the two kinds of observable quantities which do not coexist as exact values. With respect to motion, these are position and momentum. The role of the observer, thus, might look as "more" determining. Yet, in both cases, classical and quantum, it is nature that determines the results in the chosen environment and fit the laws of physics. The results remain objective, that is, predicted, statistically, in the quantum world and deterministically in classical theory, independent of the will of the observer. The objective nature of physical knowledge in the quantum theory is often confused and explained [42–44] (pp. 403–405), [45]. Physics principles are observer independent, while their realization is determined by the specific context chosen by an observer. By observer physicists mean a particular frame of reference and the affiliated to it apparatus of measurement. We may summarise this conceptual evolution in the flowchart of Figure 1.

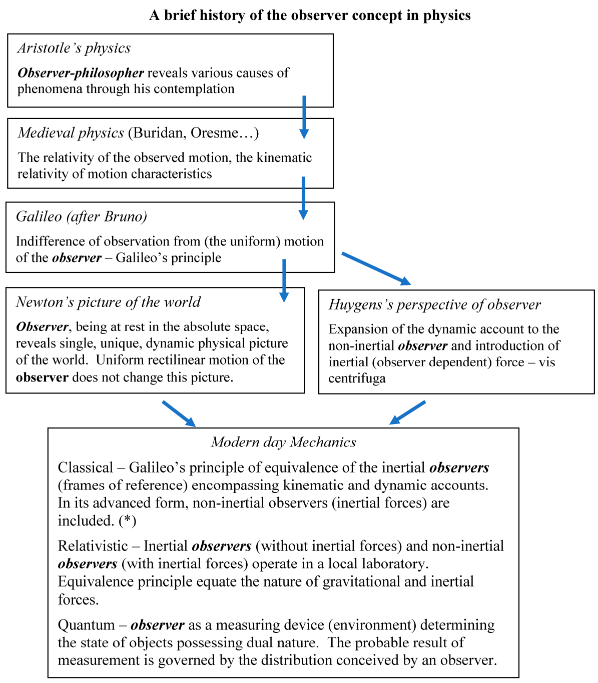



**Figure 1.** The evolution of conceptual meaning of the observer in physics. (*) Regarding the schism between the school and the advanced form of classical mechanics see the following discussion and the details in [32,34].

## *2.3. The Observer in Physics Teaching in School*

Despite the high conceptual importance, commonly, observer dependent concepts do not receive appropriate treatment in physics classes. To a great extent, the school curriculum does not go beyond the Newtonian perspective of the 19th century. The treatment of such basic concepts as distance, displacement, velocity, forces, energy, and work, often ignores their relative nature, making the teaching essentially deficient. Is this an appropriate policy?

Teaching about changing seasons is an indicative example. It usually takes place in our elementary schools, and there, it is presented solely in the heliocentric frame of reference. This "scientifically correct" account strikingly contradicts the direct observations of the pupils located on the earth's surface, which is the geocentric frame of reference, equally legitimate scientifically, as if we are still in the debate with the church in the 16th century. Common instruction often ignores the direct perception and thus is destined to face resistance by students [46,47]. Relating the accounts by *two* observers could remove this artificially created barrier to understanding. Has anybody consider the other option, combining two observers' perspectives in teaching? Meanwhile, in reality, teachers usually stay with the "solely correct" single view, no matter what [48].

One may assume several factors to justify neglecting addressing observer dependence. One factor is that this account of more than one perspective is beyond the *students' cognitive abilities* at the elementary school age—the subject of developmental psychology [49,50]. The students could be too young to consider relative concepts for the need of analysis from the perspectives of different observers clashing with their natural egocentric account. But a research-based examination of this assumption across the age range is lacking.

Another feature of the school physics curriculum is seeking a clear *separation between classical and modern physics*. For years, a somewhat similar separation was commonplace in teaching mathematics: elementary algebra, geometry, trigonometry—the area of secondary school education, while calculus, analytical geometry and so on—the university area, tertiary education. This tradition was revolutionized about a decade ago. Classical mechanics provides a situation calling for change for a different reason–the progress in understanding the same content. The latter changed continuously after Newton in the 17th century [51,52], and its present form includes inertial and non-inertial observers, inertial forces, and the equivalence principle [53–55]. The inclusion of multiple observers into the curriculum does not necessarily presume dealing with the relativity theory per se, though it definitely brings students closer to the concepts of modern physics barely touched in high school, if at all, especially when physics presents an elective subject in high school and reduced in middle [56,57]. It looks like a decision to keep the students at a distance from any hint of modern physics content, as if assuming that it is above the abilities of school students. This assumption, however, has to be tested. Does it draw on a lack of proper mathematical tools? As a categorical claim, it is a false assumption too. Researchers reported about the ideas, ways and extent of introducing quantum theory in schools [56–58]. At the *introductory* level of observer-dependent concepts, there is no such barrier in *classical* mechanics.

Furthermore, one may hear that classical physics, the Newtonian mechanics, is in line with students' intuition whereas the ideas of modern physics go against this intuition. Thus, the *contradiction with intuition* is assumed to be another barrier. However, the accumulated research evidence clearly testifies about numerous misconceptions regarding the *classical* physics, which strongly contrasts with intuition [15,16,59,60]. For instance, it was observed that even good students spontaneously invent inertial forces, not a Newtonian concept, while they were never instructed in them in their classes [61].

As to pedagogy, students showed a better understanding of concepts if instructed using operational definitions. For instance, the operationally defined *weight* appeared to be more in resonance with students' intuition than the traditional gravitationally defined weight, causing a remedy of common misconceptions [22–24]. *Force*, operationally defined by the elastic deformation, in addition to the deflection of a body from a straight path motion, can serve as another example. Why not test the compound definition of force, at contact and at a distance, bringing the student to dealing with non-inertial (accelerated) observers, as Huygens did? Here, we depict such a teaching and tested whether school students were able to apply multiple depictions of a physical situation—observer dependent account—including the acting forces. Our experimental results depicted in the following report support the pertinent changes to the curriculum and suggest new content items of teacher training and corresponding assessment tools.

### *2.4. Intuitive Knowledge and the Observer Concept*

The intuitive account by a layman is normally performed in the frame of reference centered in his/her body, which may be called the "personal frame". Piaget called this cognitive preference egocentrism [50]. It implies involving individual perception and derived ideas. An example of this reality are children's ideas regarding the shape of the Earth [46,47]. Teachers invest much effort to persuade students to overcome, reject, or discredit the naïve interpretation of the observed reality, often without any bridging to the heliocentric view [48].

We consider here the concept of force. In fact, the personal frame of reference is usually non-inertial, people move with varying acceleration while walking, running, moving in a car, etc. This reality implies the invalidity of the Newtonian account of the forces "perceived" (naively interpreted)—not a good start to learning if simply ignored. As understood by Huygens, a person on a rotating disk naturally interprets the situation in terms of a force pulling objects radially outside, while the theoretical account of the same situation by an external observer, standing next to the disc, does not require such a force. That is to say, her account could be Newtonian. Similarly, a passenger in a vehicle that stops abruptly declares that she "feels" the force throwing her forward. Teachers, however, usually try their best to falsify such a force or just ignore it. A meaningful learning it is not. Ignoring this mismatch of the personal interpretation and the presented theory, a simple neglecting of tactile experience without explanation does not help. Confusion and misconceptions are guaranteed [59,60].

Teaching about weight, as a force, is also indicative in its relation to perception. Several studies inform us that its popular Newtonian definition as the gravitational force exerted on a body is problematic as contradicting the perception of *heaviness* normally associated with weight [24,61]. Accordingly, intuition identifies weight with heaviness. This is also the original meaning of the term *gravity*, which people have used for thousands of years. It was revealed how being unaware of the issue of observers, students mixed the two perspectives of inertial and non-inertial observers, employing different observers, inside and outside the coasting vehicles, satellite cabin [22,23]. Such environments as an orbiting spacecraft, an accelerated vehicle, or amusement park facilities, provide endless confusion regarding weight [62]. The teacher is in an extremely difficult situation if the variation of observers is not part of the curriculum, which considered only the original Newtonian perspective; its difference with the present form of classical mechanics remains unknown.

### *2.5. Concept Definition and the Concept of Observer*

Science philosophers [63–66] and science educators [67–70] explicitly argue for the essential need to strictly define physical concepts. Moreover, the underrating of concept definitions in the Bloom taxonomy of cognitive activities was criticized and deconstructed in education [71,72]. Historically, in science, the theoretical definition of concepts often undermined the statements regarding the ways of their measuring. Mach was among the first to understand the fundamental role of measurement which is beyond a mere illustration of a theory [31]. Modern physics embraced this understanding which was elaborated in the philosophical approach of *operationalism* [63,73] and further refined, drawing on the obvious need of theoretical concepts to manipulate and interpret any measurement, that is, using a theory. Not only, in fact, many physics concepts are not measured directly (e.g., field) or not measured at all (e.g., wave function) [74]. However, the operationally defined concepts (simultaneity, length, time) are in the basis of Einstein's theory of relativity, and the operationally defined observables are in the basis of the quantum theory.

The resolution of the challenge to decide "what is first?" (what is more fundamental?) comes from the understanding that being a product of reciprocal construction, physics knowledge equally needs both theoretical and operational definitions of a concept as a complementary pair of *equally* fundamental components. Each concept, therefore, requires at least two types of definition, nominal (theoretical) and operational (epistemic). The two definitions should be mutually consistent, thus constructing the holistic meaning of a concept [66].

In education, the inclusion and emphasizing of operational definition are especially important for establishing conceptual meaning, being highly appealing to the learner. Sometimes it is in contrast to theoretical definitions. For example, in the ongoing competition between the popular gravitational and operational definitions of weight, ignoring the operational definition inspires numerous misconceptions stemming from the intuitive conception of weight as the perceived heaviness (the original meaning of *gravity*), which are especially prominent at the state of weightlessness in free fall [75].

Addressing the observer's account of dynamics brings us to the concept of force. The definition of force as a measure of *interaction* immediately separates between inertial and non-inertial observers. The latter practices inertial forces which are non-interactive, but can be measured by a force meter. Therefore, the operational definition of force as measured by elastic deformation of the force meter, regardless the kind of observer, is required for the introduction of the observer into mechanics' curriculum.

### 2.6. Space of Learning and the Observer

In physics teaching, particular emphasis should be given to creating an appropriate *space of learning*, which presumes presenting the subject of learning through variations of its essential features and the comparison between them [33,76]. In particular, considering phenomena in more than one frame of reference allows emphasizing the universal meaning of the concept considered. It surpasses a mere *kinematic* variation (velocity dependence on the observer) and includes *dynamic* relativity (employing inertial forces). For example, an analysis of the active forces by the observer inside an orbiting space station contrasts such analysis by the observer on the Earth's surface. These two accounts create an extended space of learning about motion and about weight/mass. The associate discussion and analysis will consider what is similar, what changes, and what remains invariant. In our use of the observer, considering the common and the different will make learning more effective and meaningful, and reveal the pivotal role of an observer in classical mechanics. In this way, the nature of scientific concepts, their observer dependence, and their ontological status are placed on the stage of learning while preventing the reification of the force concept.

### 2.7. The Intention of This Study

As we have already mentioned, since the 20th century, the observer concept has come to the fore in physical science, waking up after a long dormancy since the 17th century. It was applied to the characteristics of motion, formulated in terms of frames of reference, and elaborated within the modified theory of classical mechanics. The latter transformation may deserve no more than a comment while providing background in addressing classical mechanics in contemporary teaching.

In school classes, teachers usually touch on the relativity of kinematic quantities, but in dynamics, that is with regard to force, such considerations are extremely rare. Indeed, Newtonian mechanics is valid solely in the inertial frames of reference (inertial observers) and deals only with interactive forces. The inertial forces were excluded from the school curriculum of mechanics thereby painstakingly preserving this tradition from the 19th century. At the same time, the classical mechanics taught at universities does not have any problem in using inertial forces, as well as non-inertial observers. Yet, the teaching keeps with the titles of "fictitious", "pseudo-forces", and "imaginary" forces barely helping in presenting their nature especially to a novice.

Here, we try to reconsider this situation in school mechanics. We introduced inertial centrifugal force and non-inertial frames of reference to the students of middle school. In doing this, we drew on the operational definition of force, often insufficiently elaborated. This change matches the modern teaching of weight concept, and promote students' acquaintance with the fundamental idea of the equivalence principle as a part of *classical* mechanics. Our approach will facilitate further learning of observer-dependent ideas of physics, classical and modern. It removes the perspective of 19th century physics, the confrontation with engineering, the accounts of phenomena saturating the media accessible to all. In all these areas, the use of inertial forces is commonplace.

## 3. The Experiment and Its Methodology

### *3.1. Rational and Research Questions*

In the theoretical part, we made several claims which require empirical clarification. Here, we describe the required experiment. In particular, we examined the feasibility of integrating the concept of observer already in the middle school, the results of such inclusion, and the impact of several observer-dependent concepts usually studied in physics classes: kinematic concepts, and forces, weight, and gravitation in dynamics. We examined student ability to account for the pertinent problems in different frames of reference, and to choose the most convenient frame in each situation. In doing this, we considered three aspects: curricular, pedagogical, and affective. Table 1 presents the derived research questions and the related methodology.

### *3.2. Participants and Setting*

Stage A. The pilot study lasted a year. The sample included 16 students in the 8th grade from the regular stream. This stage provided early information regarding the adequacy of the materials and their appropriateness for middle school students, and an indication that the students are capable to learn observer-dependent concepts and apply them in simple situations. The new teaching materials were delivered to students in 12 activities of 1.5 h each.

To increase the reliability of the experiment, each session was delivered separately to two equal groups of 8 students. The groups were assessed by a pre- and post-test. In addition, students' personal feedback was collected.

Stage B. The second stage of the experiment was conducted over two years. It involved 9th grade students from two classes over two sequential years. Altogether, 117 students comprised four groups. Each year there was an experimental and a control group; 61 students in the experimental groups and 56 in the control groups.

To initially certify equivalence of the experimental and control groups, Levene's test of variance and the *t*-test for independent samples were applied to the data of the students' mathematics test that was available at the school. We took the results of testing mathematical knowledge as an indicator of students' abilities of learning science. Such tests address basic logical skills and tools required in physics. In particular, such tests check the familiarity with algebraic and graphical description of events essential for learning the topic of observer in physics.

The math scores of the experimental group (84.8, s.d. = 10.9) and the control group (83.0, s.d. = 10.5) were not found to be significantly different [$t(113) = 0.89$, $p = 0.377$, and $F(113) = 0.167$, $p = 0.683$] indicating similar abilities of the experimental and control groups. involved at stage B of the experiment.

The new class teaching addressed students in 12 activities, 1.5 h each. The teaching considered kinematics and dynamics content (the concepts of velocity, distance, displacement, forces and gravitation) which, in one way or another, possessed observer dependent nature. The teaching in the control groups was consistent with the regular curriculum. The first author taught both groups: The experimental and the control groups. To increase the reliability and visibility of the expected changes, the activities of a more regular character related to the account of motion (sessions 5, 6 (Table 2)). were taught by another teacher of the school, in both experimental and control groups.

**Table 1.** Research goals and questions.

| # | Research Questions | Applied Methodology |
|---|---|---|
| 1 | Feasibility and Ability<br>What is the evidence that middle school students are able to learn observer-dependent concepts and handle their application? | Testing the problem-solving success, ability of drawing force diagrams, graphs of velocity and displacement dependence on time by different observers, and students' choosing convenient frames of reference. |
| 2 | Efficiency of the new teaching<br>To what extent is the observer-dependence mastered by students? | Comparison between the test results of students from the research group (enhanced observer-dependence) and the control group (taught the regular curriculum). |
| 3 | The success of learning<br>What are the features of students' knowledge regarding observer dependent concepts?<br>What is the relationship between the initial and the post instructional knowledge in this domain? | Pre-test for mapping students' naive knowledge of the observer dependent concepts.<br>Examining the relationship (significance and statistical correlation) between students' naive knowledge and their achievements in the post-test. |
| 4 | The affective impact<br>What is the impact of teaching observer-dependence on students' engagement in lessons, and their attitude towards physics and interest in learning? | Collecting data on students' learning experience, the evidence of affective impact of the teaching, features of students' learning and their attitude towards physics. |

The same pre-test was administered to the experimental and control groups while the concluding tests were different. For the different teaching content, we conducted post-test-A on the experimental group and post-test-B on the experimental and control groups. Feedback comments were collected only from the experimental teaching group.

### *3.3. Learning Materials and Teaching*

In light of our intentions, we developed new curriculum content for 12 double-period lessons (of 90 min) for middle school students, enriched with the enhanced presentation of the observer-dependent concepts. The curriculum expanded on the topic of weight and gravitation for its being especially illustrative of the aspects of invariance, observer dependence and concept definitions. The class teaching for all the participants was of the kind common in our middle schools, including discursive elements, using illustrative pictures and animations, illustrative examples. Significant and multifaceted novelty of the experimental teaching was in its inclusive and innovative content incorporating features of history and philosophy of science (Table 2).

**Table 2.** The content of the experimental teaching.

| # | Activity Subject | Activity Content |
|---|---|---|
| 1 | The relative nature of scientific concepts used in the physical account | Aristotle's account of feature variation (cold-heat, heavy-light). Quantitative and qualitative descriptions with respect to accuracy. "Anchors" guiding in characteristic features ("heavy body" in specific experience). Relative and absolute difference. Multiplicity of perspectives and interpretations |
| 2 | Definition of important concepts and ideas | Definition of observer and frame of reference. Invariance (constancy) versus relativity. "Physical law" as an invariant. Velocity as a relative concept; Galileo's principle of relativity. |
| 3 | Aspects of observer dependence | Theoretical and operational definitions. Inertial motion and observer dependence. The history of the geocentric and heliocentric models. Plato's 'Cave Parable', observer dependence and reliance on senses. "If a tree falls in the forest and no one is there, did it make a sound?" Newton and his relation to the observer. |
| 4 | Account of Motion | Basic concepts and their computation. Choice of the axis and its freedom. Distance and displacement, velocity and acceleration. Uniform and inertial motion. Distance, displacement, and velocity as relative concepts |
| 5–6 | Problem solving<br>and changing perspectives on the given motion | Analysis, graphing and computational solution of motion problems (distance, displacement, and velocity as a function of time) in relation to inertial observers. The invariance of physical laws and different numerical accounts. The choice of the convenient frame of reference. |
| 7–8 | Interaction and forces (the Newtonian paradigm) | Force as intensity of interaction. Newton's third law. Inertial observer. Types of forces—normal in contact, friction (kinetic and static), gravitation at a distance. The net force. Operational definition of acceleration. The first law of motion. The second law of motion. Force diagram for inertial observers. |
| 9 | Force as a relative concept. | Force operationally defined. Observers disagree on the state of motion. Implication regarding forces identification (Huygens' case of an observer on a rotating disc). Centrifugal force as an observer dependent construct |
| 10 | The dynamical account of motion in inertial and non-inertial frames of reference | Force account as observer related: in a free-falling elevator, in a suddenly stopping or accelerated train/car, in riding a bus on a turn. Force diagrams in these cases by different observers. Accelerated frame of reference and the "feeling of force". Inertial force and interactive force. |
| 11–12 | Gravitation | Manifestation of gravitation (planets, the Moon, the tides, falling) and Newton's law of gravitation. Orbiting as continuous falling. Motion inside a satellite, floatation, the presence of gravitation and lacking of gravity. Newton's cannon. Force diagrams for the objects in a satellite by different observers. Force-meter and weighing. The operational definition of weight and its difference from gravitational force (the weight-lessness in a spacecraft). Weight and gravitation as forces applied to different bodies. |

### *3.4. Data Collection and Assessment Tools*

Data collection at both stages of the study was done by means of four open-ended questionnaires (pre-test, two post-tests and feedback questionnaire) (Table 3).

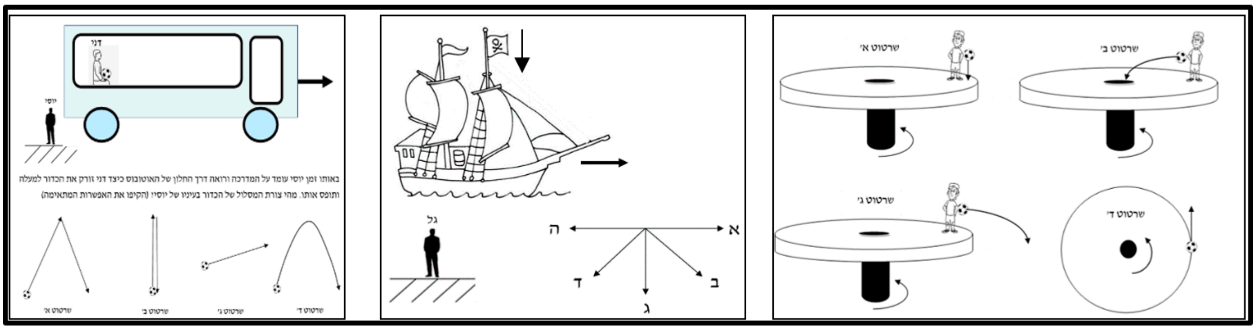
**Table 3.** The sequence of assessment activities in the study.

| Stage | Research Tool |
|---|---|
| A | Pre-Test |
| | Post-Test-A |
| | Collected Feedback |
| B | Pre-Test (experimental and control groups) |
| | Post-Test-A (experimental teaching group) |
| | Post-Test-B (experimental and control groups) |
| | Collected Feedback (experimental teaching group) |

We applied our assessment in accordance with the goals using qualitative and quantitative questions. Their validity was confirmed by three colleagues, who are senior physics educators. The qualitative questions were of the open-ended format which increased the diversity of the collected information. To increase reliability of the probe, each aspect of inquiry was addressed in more than one question. Seeking objectivity in the assessment of the post-test results, its criteria were prepared in advance and were agreed on by all three evaluators.

#### 3.4.1. Pre-Test

The test included 14 open-ended questions addressing various situations (Figure 2). We aimed to probe students' initial knowledge regarding observer-dependent concepts. In particular, their ability to consider a situation from different points of view and to analyze them. Students' verbal answers were qualitatively analyzed in seven aspects (the preference of internal or external observer; the validity of different observers; the capability to imagine the views of different observers, etc.). In the quantitative analysis, scores were calculated according to established criteria.




(**a**) (**b**) (**c**)

**Figure 2.** Illustrative fragments of the pre-test. The students were asked to choose motion path of a body (the text in the figure): (**a**) a ball is tossed up inside the cabin of a uniformly moving lorry as seen by an observer on the ground; (**b**) a flag descended from the mast of a ship moving at a constant speed as seen by an observer on the ground; (**c**) a ball is dropped by a person standing on a spinning disc. The text in the figure marks the sketches.

#### 3.4.2. Post-Test-A

The test included 14 open-ended questions (computational and narrative) addressing observer-dependence. We probed students' knowledge, their ability to consider physical systems in different frames of reference and their ability to choose the most convenient one. Students' success would indicate such an ability of using the pertinent knowledge.

The answers of each student were examined separately for each of the domains: kinematics (4 questions), forces (4 questions), weight and gravitation (6 questions). The answers were assessed according to several criteria, as will be detailed in Table 4.

Our statistical analysis informed us regarding the relationship (significance and correlation) between the naive and constructed knowledge (pre- and post-tests), indicating the impact of teaching. The analysis of multiple linear regression distinguished between the contribution of naive knowledge (pre-test) and learning capabilities (math grades) to the overall success in learning, as evidenced by the data.

#### 3.4.3. Post-Test-B

The second post-test compared between the experimental and control groups, the students' knowledge and skills regarding the considered concepts of the traditional curriculum. The test included 17 questions: kinematic (7 questions), forces (5), weight and gravitation (5). A *t*-test for independent samples was applied to determine the impact of instruction indicated by the difference between experimental and control groups, if any.

#### 3.4.4. Attitude Feedback

The anonymous questionnaire was used to evaluate the affective impact of the experimental teaching; students' satisfaction with this class experience; their attitude towards learning physics; interest in the subject, and their engagement in the process of learning.

## 4. Main Findings and Analysis

The data analysis produced rich quantitative and qualitative results. The results addressed the concept of observer held by the middle school students prior to any instruction on the subject and after the experimental teaching. We present the findings of the second and main stage, Stage B, of the study. In this, we draw on the data [77] and analyze their implications, categorized in accordance with the goals of this study.

We preface our findings by saying that in the data analysis we did not follow the individual development of the students. Instead, we rather intend to see the relevance of the results regarding the student population as a whole with the implications for the curriculum, which will suit a great variety of individuals.

### *4.1. Pretest*

In the course of analyzing and interpreting students' responses to the pretest questions, we established several categories which represent students' explanations in their answers (Figure 3).

This test results were analyzed in two ways. In the first, we evaluated the frequency distribution of each category in all the answers (N = 106 in 13 questions) to create a picture of knowledge prior to the experiment. The data were categorized to represent the subject of interest (Figure 3). As can be seen, category *a* of this knowledge is fundamental and simple. It superficially includes categories *d*, *e*, *f*, *g* that refine it in one way or another. This category indicates that for the majority of 85% (Figure 4), observer dependence is recognized prior to any instruction. For instance:

Question: Guy claims that the earth we live on is in the shape of a sphere.

Ben claims that the ground is as flat as a round disk.
Who do you think is right? How do you know?
What is the reason for the disagreement between Guy and Ben?

Students answered:

- Guy is right, because I have seen images of the Earth from a distance and it is really a sphere (Category *c*).
- Ben trusts what he sees, and he sees that the earth is flat. It happens that the Earth is a large star relative to humans, and we cannot appreciate its shape when we are on it (Category *a*).
- Actually, both of them are right, the disagreement stems from the different spatial perception by the two. Ben perceives reality directly and Guy treats it in a more inclusive way. Each of them holds a view from a different place (Category *d*)

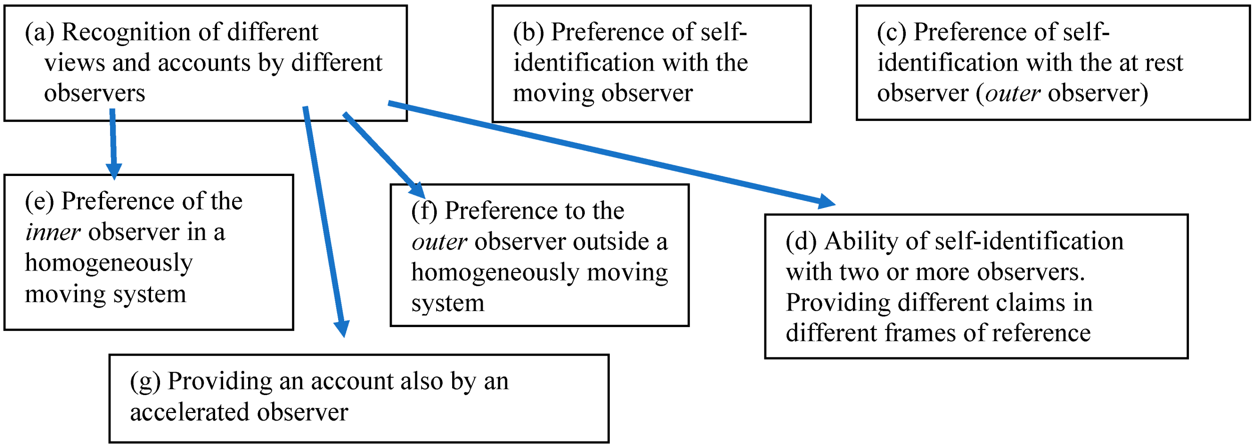



**Figure 3.** Students' preferences in providing answers to the pre-test questions organized in the introduced characteristic categories.

The frequency distribution of the categories in the whole data is presented in Figure 4.

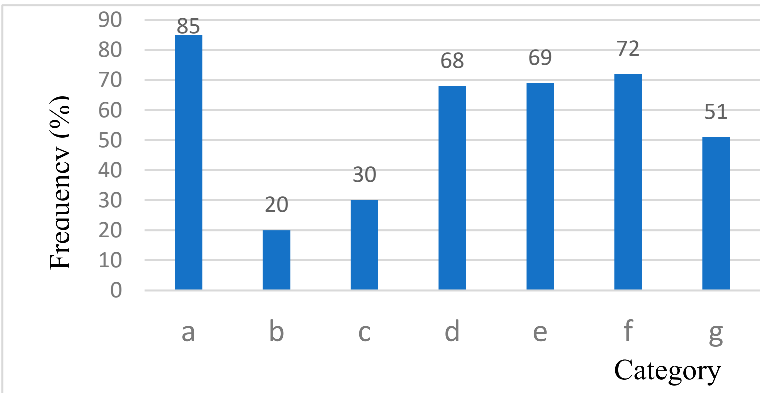



**Figure 4.** The distribution of average frequencies (%) of the categories in the whole population of the participants.

Apparently, the frequencies do not amount to 100%. Students' naive knowledge is not self-consistent as the scientific knowledge is within a theory. Their knowledge is context/situation dependent. However, certain contexts, such as the heliocentric *picture* of the world, are usually taught as an observer independent fact, while often ignoring the appearance to different observers. In another context, however, the same student could identify him/herself with a moving observer. In the context of a moving train, for instance, students considered the situation referring to inner and external observers.

As we observe, the preference to a single view of a moving observer (category *b*) and the observer at rest as a single view (category *c*) were rather rare. The self-identification with a moving observer was frequent (*d*, 68%). Addressing the inner moving inertial observer (*e*, 69%) and inertial observer outside of the moving system (*f*, 72%) were rather frequent. Approximately half of the students' addressed the view by an accelerated observer (*g*, 51%).

Furthermore, in order to test the equivalence of the experimental and control groups we had to consider individual performance of the students in each group. For this, we calculated the individual scores, which reflected the distribution of applying the categories of Figure 4 by each individual and calculated their averages in each group. Their comparison confirmed that there was no significant difference between the average scores of each group, the experimental (70%) and control (68%). The level of identity was represented by the parameters $t(104) = 1.05$, $p = 0.293$ for the scores and $F(104,1) = 0.796$, $p = 0.374$ for the deviations.

Thus, we preformed identification of the categories and found their distribution in the naive knowledge regarding observer-dependent concepts in different situations. The results indicated wide familiarity with relative concepts, and the ability to identify oneself with several observers in the same context, to change perspectives and consider situations from several reference systems, to provide a qualitatively descriptive account in several frames of reference. These results are consistent with the reports regarding naive knowledge in previous studies, such as the spontaneous self-identification with the inner or outer observer in the context of a satellite [23]. Our data confirmed that certain situations were especially provocative for self-identification as a non-inertial observer. Other researches pointed to similar tendencies other contexts (e.g., rotation disc [19] and water container [61]). With these results of the pretest, we moved to the next stage of the study, in which we tried to surpass the account relying solely upon inertial observers. In doing this, we could assume that such an approach appeals to the ideas not completely new but one way or another familiar to the students. One may say that such knowledge is located in a ZPD (zone of proximate development [78]) of school students.

### 4.2. Post-Test-A

After the experimental instruction, we examined the pertinent abilities of the students to consider questions in the topic domains of kinematics, forces, and weight/gravitation. Here we present the categorized results of the students' performance (Table 4).

**Table 4.** Post-test A results regarding students' manipulation of observer dependence.

| Topic | The Abilities Examined | Average Scores (%) |
|---|---|---|
| Kinematics | Manipulation with the graphs of time dependence of displacement, distance and velocity in different frames of reference | 86 (25 *) |
| | Calculation of displacement and distance by three inertial observers | 76 (31) |
| | Algebraic accounts of motion by three inertial observers (computation of time to the meeting) | 83 (30) |
| | Understanding of legitimate accounts by different observers (variants and invariants) | 79 (35) |
| | Choosing the most efficient frame of reference | 78 (32) |
| | Ability to relate between the graphs by different observers | 69 (24) |
| | Describing trajectory by different observers | 92 (18) |
| | Weighted average | 80 (18) |
| Forces | Providing examples of force dependence on the observer | 64 (41) |
| | Distinguishing between theoretical and operational force definitions | 86 (23) |
| | The force account by an observer on a rotating platform. Inertial force. | 81(33) |
| | The force account of the rotation motion by an inertial observer | 77 (34) |
| | The force account of linearly accelerated body by a non-inertial observer | 83 (23) |
| | The force account of linearly accelerated body by an inertial observer | 79 (18) |
| | Explanation and implementation of Galileo's principle of relativity | 95(06) |
| | Weighted average | 76 (20) |
| Weight and Gravitation | Weight and gravitation—the account by operational and gravitational definitions | 73 (23) |
| | Explanation of Newton's cannonball thought experiment | 79 (28) |
| | Explanation of weightlessness in a satellite by an observer at rest relating to the Sun | 63 (40) |
| | The force account for an astronaut orbiting the Earth and for a person in a free-falling elevator by the observer at rest on the ground | 74 (16) |
| | Explaining weightlessness by an astronaut in a satellite and by a person in a free-falling elevator | 85 (30) |
| | Identifying the forces acting on the astronaut orbiting the earth and acting on a person in a falling elevator by an inside observer | 81 (24) |
| | Understanding up and down directions as operationally defined relative concepts | 89 (21) |
| | Weighted average | 81 (15) |

* Standard Deviation.

Given our students affiliation to middle school, the variety of abilities shown by them was significant. 9th grade students succeeded in providing observer-dependent accounts with regard to kinematic and dynamic concepts. The students produced graphs of time dependence of displacement, distance, and velocity in different frames of reference, drew force diagrams with respect to a uniformly moving and accelerated observer, could chose an efficient frame of reference, and used complementary definitions of weight. The score distribution (Figure 5) indicates significant learning and conceptual understanding applied to the representative physical settings.

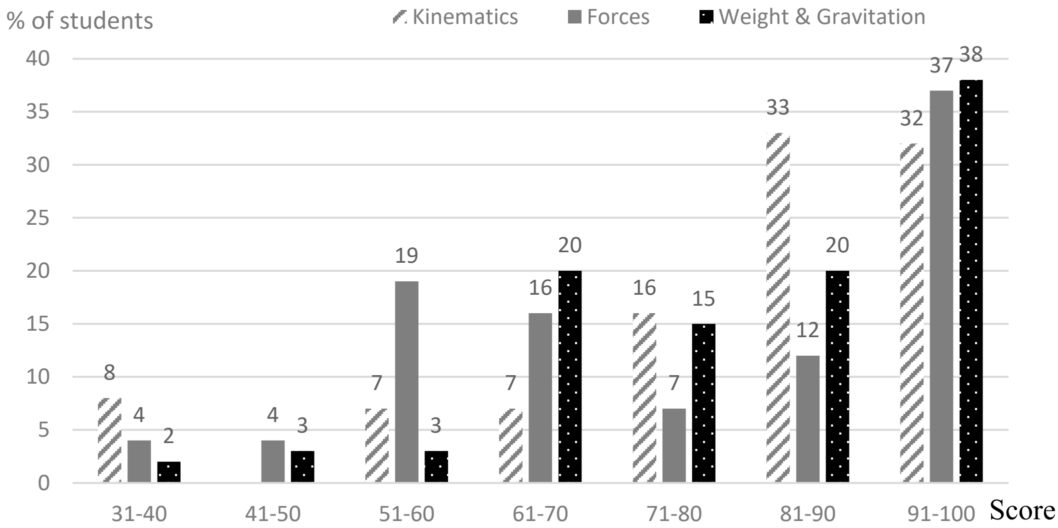



**Figure 5.** Post-test A distribution of scores (%) in the experimental group.

The following Figures 6–10 illustrate the correct answers provided by the students in this test. It is difficult to identify the details in the photos (beyond the foreign language used). We display them to show how thoroughly the students answered to the questions.

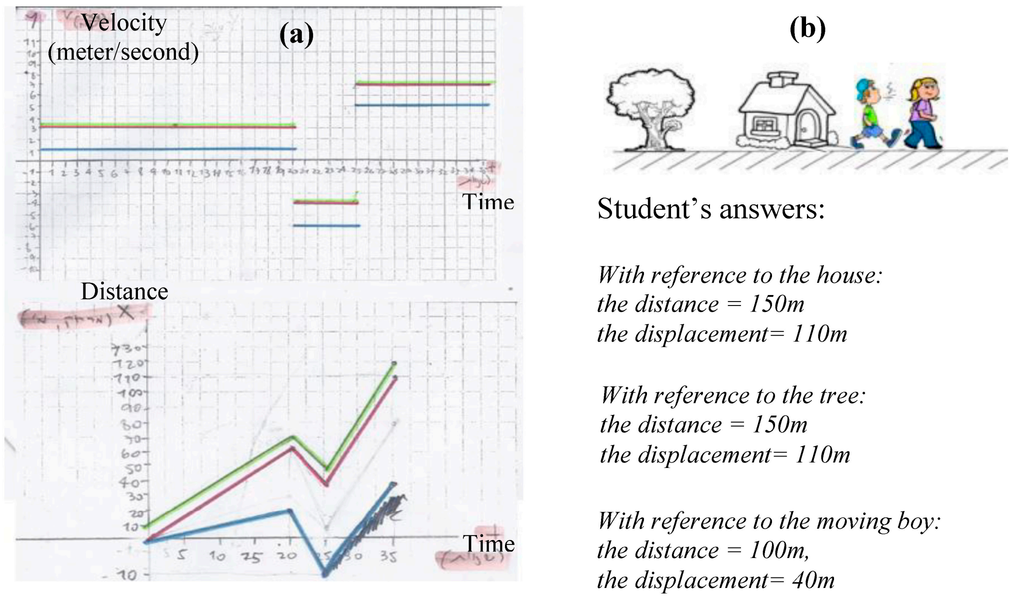



**Figure 6.** (**a**) Examples of the graphs of velocity (meter/second) and displacement (distance) versus time for the girl walking back and forth at different speeds with respect to three observers (in the house, next to the tree −10 m aside, the boy walking at 2 m/s to the right–the lines of different colors); (**b**) Example of a student's answers regarding the distance and displacement of the girl with respect to the same observers.

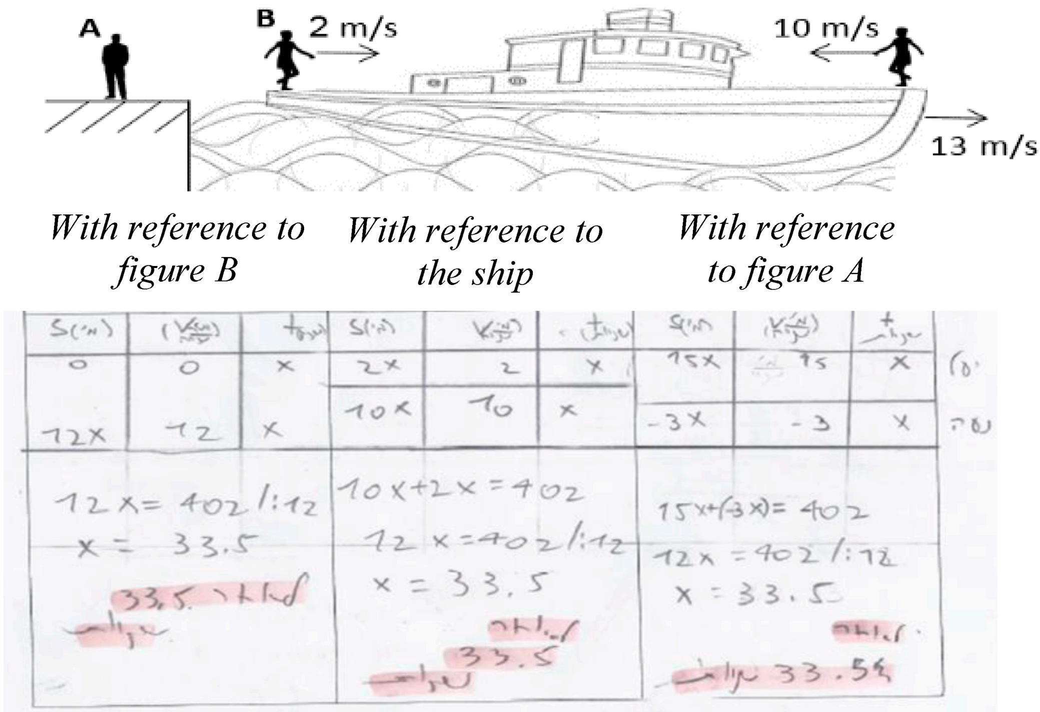
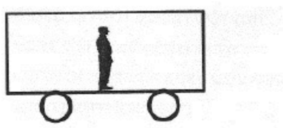



**Figure 7.** The illustration of computation of the time required for two travelers on a ship to meet in view of three observers provided by the students. The answer includes three different equations with the same result for the time—33.5 s–emphasized by the students.

**Q.** Danny travelled in a train. As the train approached the station, the driver pressed on the brakes, and Danny fell forward. Please explain this event



*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 any force on the passenger (the right diagram below).*

*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 Fi (the left diagram below).*

**Q.** Draw the force diagram for the passenger

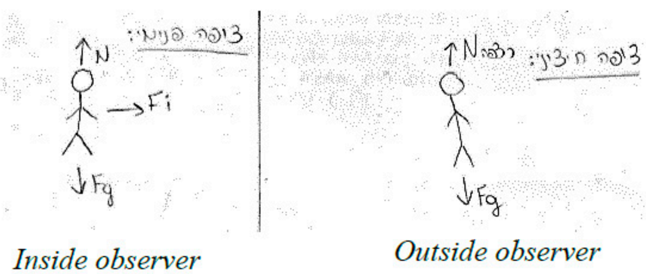



**Figure 8.** Student's answers regarding the reason for falling forward in a stopping train affiliated to two observers, inside and outside the wagon. The English translations of the students' identifying comments are added below the sketches.

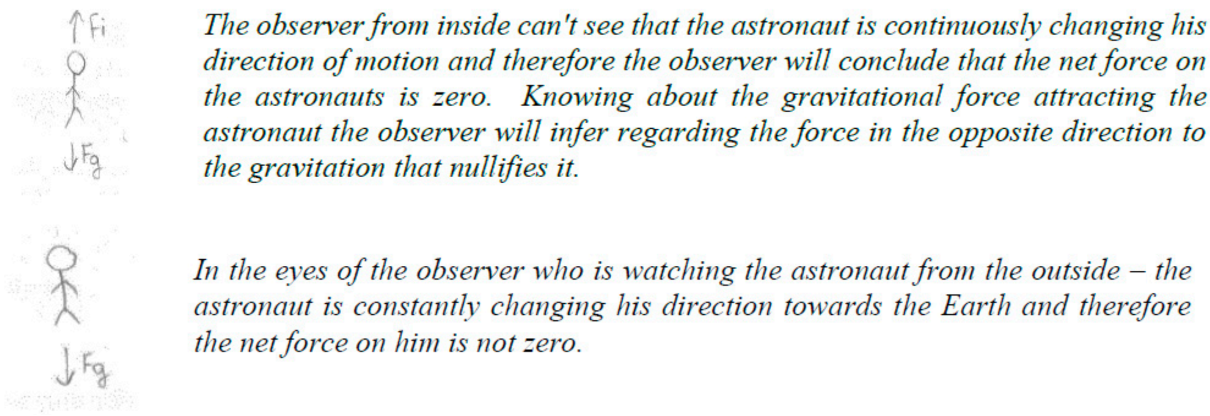



**Figure 9.** Force diagrams and their explanations regarding an astronaut orbiting the Earth in reference to two observers as provided by a student.

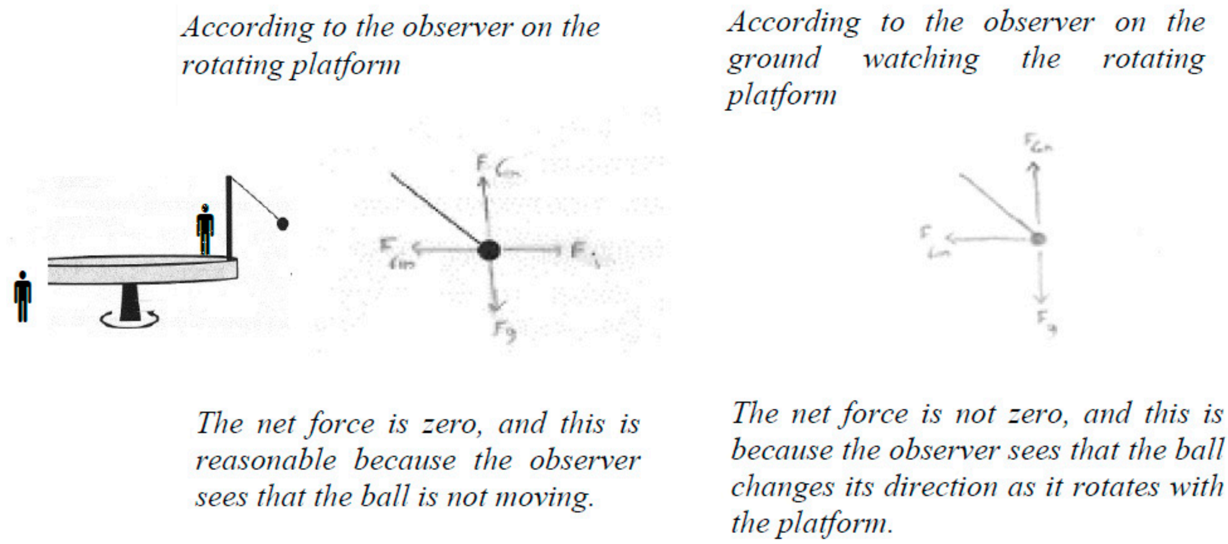



**Figure 10.** Assigning forces ($F_g$–gravitational force, $F_i$–inertial force, $F_{thread\ component}$–vertical and horizontal) acting on the ball rotating with the disc by two observers, on the disc and off it, as was provided by a student.

As we observe here, the students showed elements of the knowledge which is usually expected in people beyond the regular school education.

Another interesting question was regarding the possible relationship between students' naive knowledge of observer dependence and their success after learning this subject in class. Figure 11 presents the correlation between the results in the pre-test and the success in post-test-A.

The analysis showed positive correlation (r = 0.57, $p$ = 0.00) indicating that students' naive knowledge seemingly serves as a factor promoting successful learning. In other words, the success of learning benefits from the "fit", or "closeness", between a student's pre-instructional knowledge and the scientific content, as taught in the class [75].

We also examined whether students' learning capabilities (indicated by their mathematics grades) presented an intermediate variable between the pre- and post-results. Figure 12 reveals the results of the regression analysis. In a multivariate regression model, the standardized coefficient β expresses the contribution of each independent variable (math or content knowledge) to the dependent variable (post instruction knowledge). The multiple linear regression showed that students' naive content knowledge was of greater contribution to the learning success than their math knowledge.

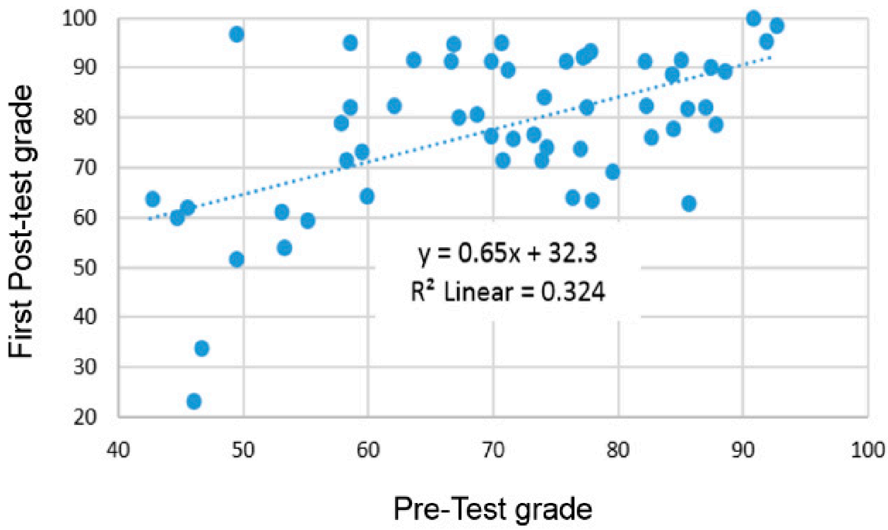



**Figure 11.** Correlation between naive and post-instruction knowledge.

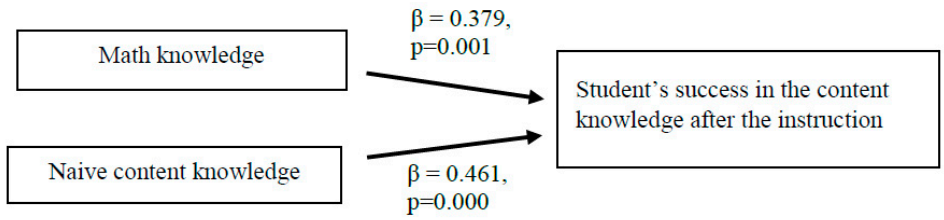



**Figure 12.** Comparison of contributing factors to the success in learning the observer dependent concepts.

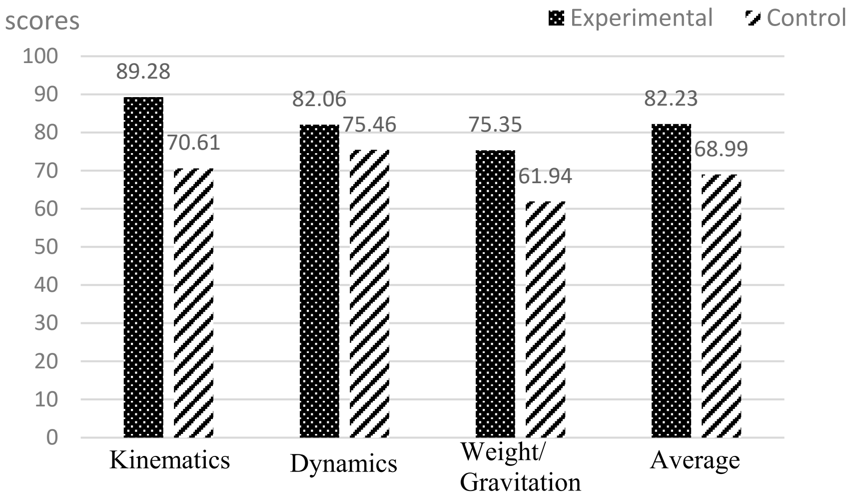
In this regard, we may mention that though it is common to take the results of testing mathematical knowledge preserved in the school database, as an indicator of students' abilities of learning science, logical skills and formal tools required in physics learning, our results testify to the non-less important naïve content knowledge.

While it is common to consider the naïve knowledge of force-motion relationship as a barrier to learning the Newtonian view [13,19,59], we have evidence here that with regard to the observer dependence, students' prior (naïve) knowledge was not an obstacle but a support. The presence of naïve considering observer dependence, if used productively in science class, apparently served as a lever for learning about observer dependence in physics. We further tested this inference statistically in the results of post-test-B.

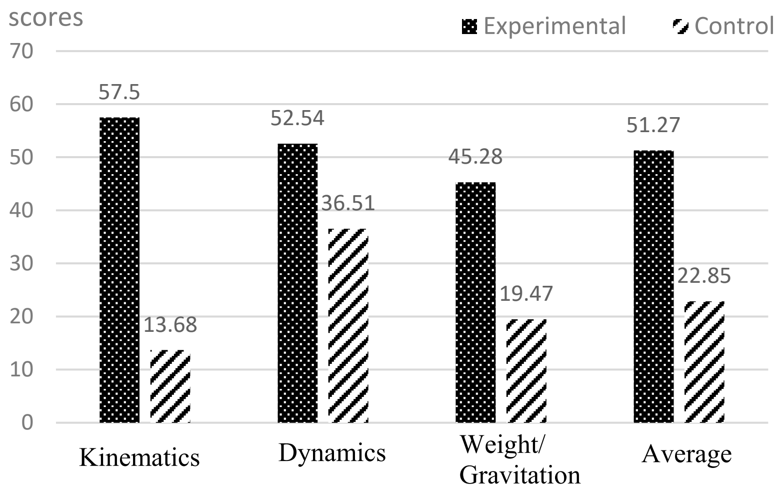
*4.3. Post-Test-B*

This test compared the knowledge and skills of the experimental and control groups regarding the items of the traditional curriculum (no mention of the observer). The score differences were segmented in two categories: (a) regular, using familiar questions and (b) challenging questions, statistically evaluated. The following histograms (Figure 13a,b) show the average scores in the topic areas of kinematics, dynamics and weight/gravitation.

Table 5 shows the corresponding results with the statistical evaluation of the difference between the experimental and control groups. The differences between the results were found to be statistically significant ($p < 0.05$) in all subjects studied and in all types of problems, except in the regular questions regarding forces.




(**a**)




(**b**)

**Figure 13.** (**a**) Average scores of the experimental and control groups (regular questions); (**b**) Average scores of the experimental and control groups (challenging questions).

**Table 5.** The post-test B results (%) of experimental (N = 64) and control (N = 53) groups and their statistical significance.

| **Questions** | **Groups** | **Grades (%) Kinematics** | **Grades (%) Dynamics** | **Grades (%) Weight/Gravitation** | **Grades (%) Average** |
|---|---|---|---|---|---|
| Regular | Experimental<br>Control | 89.28 (20.05 *)<br>70.61 (24.37) | 82.06 (25.59)<br>75.46 (24.73) | 75.35 (21.81)<br>61.94 (24.78) | 82.23 (17.20)<br>68.99 (17.35) |
| | *t*-test → | $t_{(111)} = 4.411$<br>$p = 0.000$ | $t_{(114)} = 1.405$<br>$p = 0.082$ ^ | $t_{(108)} = 3.017$<br>$p = 0.002$ | $t_{(115)} = 4.129$<br>$p = 0.000$ |
| Challenging | Experimental<br>Control | 57.50 (34.84)<br>13.68 (22.23) | 52.54 (39.61)<br>36.51 (36.13) | 45.28 (43.52)<br>19.47 (31.94) | 51.27 (23.37)<br>22.85 (21.83) |
| | *t*-test → | $t_{(111)} = 8.060$<br>$p = 0.000$ | $t_{(114)} = 2.259$<br>$p = 0.013$ | $t_{(108)} = 3.581$<br>$p = 0.001$ | $t_{(115)} = 6.115$<br>$p = 0.000$ |

(*) Standard deviation; (^) Insignificant difference.

The comparison between the two groups clearly shows that the integration of observer-dependence theme helped students in achieving more mature conceptual knowledge of classical mechanics. It provided students with better tools for the more meaningful learning of the pertinent content as manifested in the significantly higher scores of the experimental group: The difference of 13 grade points in the questions of familiar type, and 28 points regarding the challenging questions.

The statistically significant relationship between the question type (regular/challenging) and the type of group (experimental/control) is shown in Figure 14. Indicatively, it shows that the average difference between the control group and the experimental group is significantly greater with respect to the questions of unfamiliar challenging content (F (1) = 16.235, $p = 0.00$).

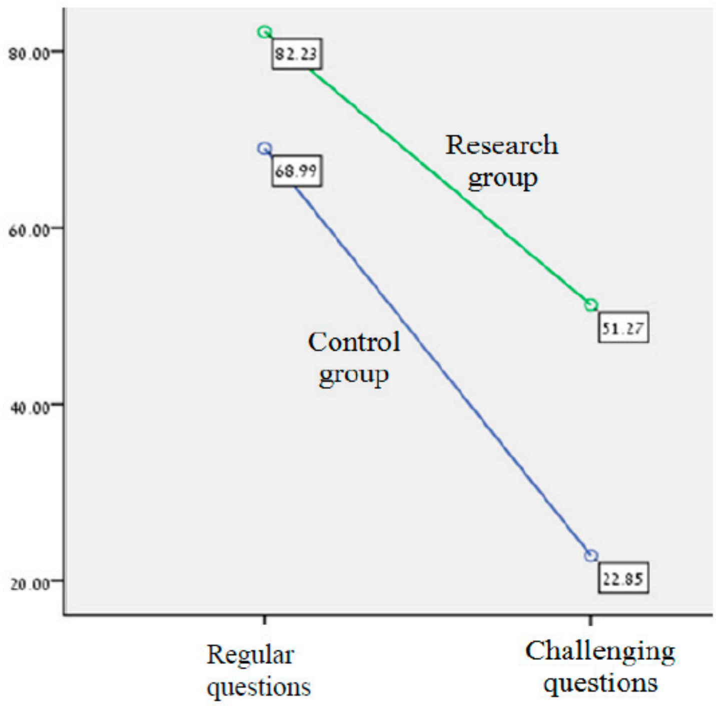



**Figure 14.** The influence of the experimental instruction on the average group score with respect to the question type (regular/challenging).

The inference of advantage holds true not just among the average scores, but in almost every question in the test. Figure 15 presents an example of students' answers (the experimental group) to a challenging question, that is, of the kind they had never seen in class.

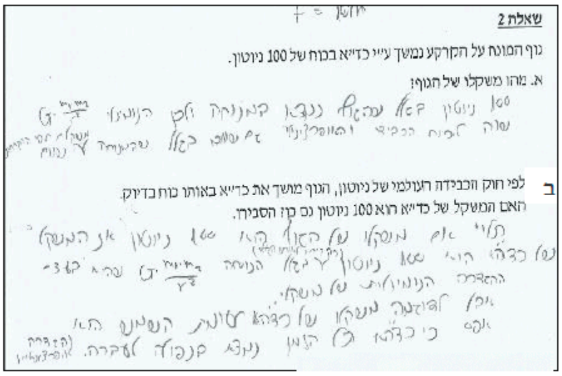
Beyond the quantitative statistical analysis, the experimental group stood out in some important characteristics including:

(i) The experimental group's answers were more accurate with accounts involving frames of reference/observer, while the students in the control group never used this concept.
(ii) The experimental group used richer vocabulary and precise concept definitions.
(iii) Many in the experimental group introduced more than one solution to each problem, for example, two explanations addressing the falling of heavy and light bodies. One student wrote:

> "both bodies have the same velocity because the earth attracts with greater force the heavier body (greater mass) and therefore the acceleration is the same as the formula F = ma implies". Using the operational definition of weight, he wrote: "as they are free falling, the weight of both is zero."

As another example, we may mention students calculating the same time interval in two different frames of reference, arriving at the same result (Figure 7).

(iv) In the questions that addressed a moving train or ship, a substantial portion (30% to 62% of the control group, depending on the problem) solved the problem with respect to the accelerated platform, in contrast to the traditional curriculum. This confirmed the previous finding that students, even those never instructed in the use of accelerated frames of reference and inertial force, in practice do employ accelerated frames and introduce inertial forces [61].




Translation:

Q.2. *A body lying on the ground is pulled by the Earth at a force of 100 Newtons.*

*A. What is the weight of the body?*

*B. According to Newton's law of gravitation, the body pulls the Earth with exactly the same force. Is the Earth's weight 100 Newtons as well? Explain.*

Answers:

*A. 100 Newton because the body is at rest and therefore its weight is equal to gravitational force* $Gm_1m_2 / R^2$*(nominal def.), and the operational weight is the same because at rest the weights are equal.*

*B. It depends. If the body weight is 100 Newtons, then the weight of the Earth is also 100 Newtons (only relative to that body) according to the nominal definition of weight.*
*But, for example, the weight of the Earth towards the Sun is zero because the Earth is falling all the time towards the Sun (according to the operational definition).*

**Figure 15.** An example of students' answers to a challenging question brought with our translation.

### *4.4. Affective Feedback*

About two weeks after the experimental teaching, the students of the group provided anonymous feedback on their attitude towards the teaching period. It served us as an additional resource of data. Students' comments included statements relating to the way of teaching and to physics in general. Most of the students (92%) indicated that the topics studied were interesting or very interesting (4–5 on the scale 1–5). We reproduce several examples of such statements which students wrote as their reflection on their new experience (the translation changed the colloquial style of the students of this age):

> "I think this expansion of material helps [the class] to be interesting and attract people to study physics." (S-1)

> "With the observer concept, it was more interesting and more challenging, more fun to learn and listen in classes." (S-2)

This general appreciation, however important, was refined by the recognition of the increased difficulty of the subject matter. 49% mentioned the issue of difficulty, whereas 80% mentioned it being enjoyable, although difficult, and 76% wrote that they would choose to study the subject, whether or not it was mandatory:

> "I think learning the subject of the observer overall is important, but for me it was difficult because I did not fully understand things. But this subject made me think about life differently." (S-3)

> "I think the benefit of the method is that it makes students understand the material better and be more interested, but it's also more to learn, so for some it's harder." (S-4)

> "I liked the fact that it really interested me. The account is more difficult but raises greater interest. Due to the learning about observer all my thinking on questions and problems has changed." (S-5)

> "The advantages of this material are that it makes you more thoughtful, but the disadvantage is that everyday things we thought obvious, can be confusing when you look at them from different perspectives." (S-6)

Students' own combining of being interested with being challenged is, in fact, of special importance. It matches the feature of the "productive complexity"—a fundamental claim that is raised in science education. It appears that this claim originally stated in the context of more advanced teaching (quantum mechanics) to high school students [79] possesses a wider validity and holds in middle school too. The fact that students themselves raised this justification for increased difficulty is especially indicative.

However, the feature of the highest importance for us was the students' praising the special nature of the topic—the *observer*. The appreciation of providing accounts by various observers presents the major positive resonance with our motivation and vision of the study. It stems from the values of physics that emerged in the latest scientific revolution of the 20th century as depicted above.

Praise for relativity was expressed in the account of active forces (by 79% of students), motion (by 49%), and weight and gravitation (by 68%). 82% indicated that solving problems in different frames of reference strengthened their understanding, especially when ultimately arriving at the same numerical answer. 81% indicated that to a large extent they would like to learn more through this teaching perspective. Students wrote:

> "I liked that there was no single correct answer to explain a phenomenon but several. The advantages in my opinion is the link to everyday life and the disadvantage is that it can be confusing. It totally changed my attitude to physics and made me want to learn and know it more." (S-7)

> "My attitude towards physics has changed because I have seen that physics is not just one view, the same answer can be reached in variety of ways." (S-8)

Altogether, practically all the students showed positive attitudes to the experimental teaching. Some specifically mentioned its relevance to the everyday experience (75%) adding interest in physics (95%). They expressed their intention to continue learning physics in high school:

> "I loved that we learned about how to see the world in different ways and how to analyze different situations. Because of the learning this year I chose to keep learning physics in high school." (S-9)

> "I was sure that physics is a very difficult stuff, full of formulas, and when I learned about the observer, I realized that physics explains life and phenomena easily." (S-10)

> "This subject [observer] connects physics to everyday life and makes it more interesting . . . I'll take physics in high school (S-11)

## 5. Discussion and Conclusions

This study presents evidence of learning of the observer concept in middle school. To emphasize its high importance, we repeat that currently, the concept of the observer, though at the core of the modern perspective of physics, is only lightly touched on in the high school curriculum, mainly in kinematics, and is totally absent in major aspects of the teaching of forces, dynamics. Inertial forces are totally banned. We questioned the appropriateness of this curricular policy theoretically and examined this subject empirically. The practical success of the experiment signified the need for a specific discourse in science education. What should be farther investigated and discussed based on our experience?

### *5.1. The Feasibility and Effectiveness of the New Teaching*

As intended, we initially examined the feasibility, the pedagogical and disciplinary knowledge benefits of the inclusion of physical accounts by different observers being in uniform motion (inertial) and even in accelerated motion (non-inertial), already in middle school. In this expansion, we first regarded the kinematics quantities: displacement, distance, velocity, and later, the dynamical quantities: inertial forces, the account of weight. In so doing, we significantly enlarged students' space of learning [76] creating what we call the cultural content knowledge [80] which resulted in its more meaningful status.

The educational significance of the results was enforced by the experiment design—two successive years in regular school classes, which resulted in a reliable assessment of the impact of the teaching. The results surpassed our expectations, qualitatively and numerically. We may conclude that the subject of observer-dependent concepts is feasible, and it deserves a more serious inclusion to the school curriculum. It is within the ability of school students to learn and handle the new concepts.

The efficiency of the introductory teaching was documented. Ninth-grade students could analyze situations qualitatively, computationally, and graphically from the perspective of different observers. This included graphs of velocity, displacement and distance as a function of time. They were able to solve motion problems algebraically while choosing the effective frame of reference. They drew diagrams of forces with respect to the naturally relevant frames of reference (accelerating car, falling elevator, orbiting satellite). In the same context, they applied both nominal and operational concept definitions of weight. The experimental group received significantly higher scores (the average difference of 28 points) in questions of an unfamiliar context involving regular content knowledge.

At the affective level, we found that the new teaching had a positive impact on the students' interest and learning engagement in class discussions. In their self-evaluation, 75% mentioned that the observer-dependence issue strengthened the relevance of physics vis-a-vis their life experience. 95% stated that physics is a very interesting subject, and 76% wrote that they would choose to study physics in their following studies. Given the regular classes, this says a great deal.

### *5.2. Curricular Representation of the Classical Theory*

It was noticeable that the answers of the experimental group were of a higher quality and conceptual maturity regarding classical mechanics. This was evident in the terminology (concepts, use of definitions, relation to the observer), the flexibility in choosing a frame of reference, a multiplicity of solutions, and the verbally richer explanations.

There is, however, another curricular aspect rarely discussed in educational research. Considering different observers, including accelerated (non-inertial) ones, is not a topic necessarily affiliated with modern physics, but is a legitimate issue of classical mechanics. The observer, the frame of reference, were not included in physics classes and the discourse of curricula design until the 20th century. This concept entered the teaching of mechanics after a certain delay following the scientific revolution in the beginning of the 20th century, under its salient impact. Until the 70s, popular textbooks usually lacked the concept of observer [81,82]. However, by the 90s, it had become a regular item in undergraduate courses on classical mechanics [54,83]. The question arises as to when the *school* curriculum will join in and follow this trend, that is, when the agenda of classical mechanics in accordance with the 19th century will be replaced with the current perception of *classical* mechanics. As is mentioned above, we did not observe any cognitive limitations which would prevent this progress on the side of students. Therefore, the only barrier remaining seems to be the lagging behind of the curricular tradition in schools, the conservatism which became obsolete already, actually, decades ago.

The advantage of the suggested step is the progression of the learner to the content *shared* with the fundamental theories of modern physics, Relativity and Quantum. The new paradigm of Discipline-Culture can facilitate this development as it suggests revealing to the learners the dialogue between Classical Mechanics and other theories through the contrast between their central ideas and accounts [80]. The concept of the observer presents an attractive item for this approach, being exceptionally rich in philosophical ideas, within and outside science. The affective impact of our experimental teaching provided convincing evidence of this aspect of the considered curricular innovation and thus invites pertinent development.

### *5.3. Curricular Relationship with Intuition*

The issue of intuition is especially interesting and complex because it is controversial. Intuition is a rather close notion to commonsense. In the considered here context of the curricular policy, however, it is preferable to address intuition of students, while in comparing their knowledge with the scientific, addressing commonsense could be more appropriate [84,85]. Furthermore, it is commonly accepted to consider learning physics from the intuitive to the scientific knowledge of a subject—a conceptual change [6,86,87]. Specifically, with regard to the concept of force, students' naïve, intuitive knowledge of the subject was scrutinized [88,89] and argued as being useful in making conceptual change [26]. Camp and Clement pointed to the way to bridge instruction to intuition through the anchoring steps [59]. Yet, a great deal of suspicion towards the intuitive knowledge quite justifiably penetrated into curriculum design. Thus, our official *Mechanics curriculum* warns our physics teachers [90]:

> ... one of the difficulties in achieving this goal is the fact that students come to mechanics classes with intuitive perceptions about motion and its causes, perceptions built from an early age during interaction with the environment, and therefore well rooted in consciousness. *The intuitive perceptions are far from the Newtonian worldview and weigh on its internalization and formation*. (our emphasis)

A similar position was observed in French curriculum [85]. Here we stop and argue for the need of further refinement and change. To the stakeholders of school science curriculum, we may say, not so fast please with such sweeping claims. It depends. There are different cases. Indeed, there are intuitive ideas in clear opposition to scientific concepts, such as, for instance, light rays, heat-temperature, and force-motion. Teachers are, then, called the students to devaluate and reconsider their naïve conception. Yet, there are also other conceptions which are wrong, but resonate with the scientific (impetus) or present a development which is legitimate, such as the operationally defined weight-gravity [70]. This study adds another kind of such concept—that of the force, also operationally defined. Operationally defined, weight and force are legitimate and given their closeness to intuitive knowledge can change the considerations of instructional strategy and content. Such concepts are game changers for the curricular designers. Why? It is highly probable that the closeness, the content affinity, causes a *cognitive resonance* between the intuition and specific instruction. Vygotsky elaborated this vision of the learning success of instruction by his concept of zone of proximal development. A similar claim was made in favor of using history and philosophy of science in science classes [91]. One may express this case as a "linear model" of the learning that emphasizes the importance of "distance" between prior knowledge and scientific content as a factor enhancing student success.

In this study, we clearly observed such a constructive resonance in learning the specific subject matter, not to mention the strong affective impact of the teaching, the positive attitude towards physics, and the increased interest of the students.

At the same time, the naïve intuition manifested itself in the control group where the students inadvertently switched between frames of reference, though they had never learned to account for situations in more than one frame. In contrast, the students of the experimental group were careful and consistent in applying reference frames and choosing them.

Moreover, while examining the correlation between naive and post-instruction knowledge regarding observer dependent concepts, we found it to be more influential than the math knowledge background/ability, for instance, in their contribution to the success in learning the observer dependent concepts. Physics is different from mathematics.

The applied-by-us teaching approach legitimized certain naïve interpretations of sensory perception and converted them to scaffolding on the way to scientific knowledge. In a way, operational definition of force in any frame of reference, also in the accelerated one, matches sense/tactile perception. This is in contrast to the popular view of considering students' intuition merely as a misleading factor and insisting on the sole use of an abstract view of an idealized imaginary observer.

### 5.4. Impact on Misconceptions

The move to the flexible status of the inertial (centrifugal) force and the operational definition of force have the potential to immunize students regarding well-known misconceptions. In effect, the observer dependent account of forces serves as a remedy for the well-known fallacy of conceptualization—the reification of theoretical concepts [92,93]. This tendency of students' perception was reported with regard to the concepts of a light ray, heat, energy and force. The new approach breaks the idea of "physical existence" verbatim (the ontological misconception of reification) of scientific concepts and emphasizes their status as solely mental tools. This feature comes to the fore and is strengthened when the *force* established for a non-inertial observer disappears for an inertial observer.

Another benefit stems from the stimulated employment of the combined, nominal and operational definitions regarding each physics concept, causing more meaningful knowledge. Applied to the *force* concept, the combined definition legitimizes *inertial forces* which potentially helps in overcoming the known misconceptions of *force-motion* and *weight-gravitation* confusion. It causes better understanding of the nature of physics knowledge, and explicitly connects the experimentally obtained quantities with their theoretical, not necessarily univocal accounts. This represents the nature of physics knowledge.

## 6. Coda

The results of this study show that the introduction of observer-dependent concepts, even in the middle school curriculum, is feasible and can serve as a powerful tool that establishes a wider space of learning. It promotes the meaningful knowledge of physics concepts stating their area of validity incorporating inertial and non-inertial observers. It provides a more mature and genuine knowledge of classical *mechanics* that creates an adequate image of science among middle school students. Besides several pedagogical and conceptual benefits, this curricular change brings to the fore the concept of *observer*, promoting the conceptual affinity of classical and modern physics. Students construct the contemporary vision of the scientific knowledge, pluralistic in nature, hitherto often ignored in teaching.

**Author Contributions:** Conceptualization, I.G.; Methodology, Validation, Formal analysis, Data curation, Investigation, Resources, B.S., H.S. and I.G.; Writing the original draft, I.G. and H.G. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Informed Consent Statement:** All the subjects involved in the study were informed about the new pieces of content they learned which were permitted by the school principal.

**Data Availability Statement:** The data were illustrated while available in the Ph.D. thesis by Stein B referred to in the list of references.

**Conflicts of Interest:** The authors declare no conflict of interest.

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