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An analysis of students' misconceptions on Special Relativity

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An analysis of students' misconceptions on Special Relativity

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Abstract. Special Relativity is one of the key theories describing our reality but its accommodation among students at different level is still a critical issue. Even after instruction, students' answers continue to be biased by Classical Mechanics. We present the analysis of high-school students' answers to open questions concerning topics on Classical Mechanics and Special Relativity showing the persistence of pre-relativistic reasoning. This study is part of an experimentation on the teaching of Special Relativity with the use of a mechanical instrument that allows students to explore by hand the effects of a change of reference frame.

1. Introduction

Understanding the way students think and construct knowledge as well as the obstacles they found is leading in design and carry out didactic actions. Different theories of learning, as for instance the conceptual change and the conceptual capture [1-2], coming from science education and learning science, help the didactic research as they depict the process occurring inside the students.

The Theory Special Relativity gave a great contribution to the development of these cognitive models [3] as it received contributions from different fields of knowledge, not only from Science but also from Humanistic culture as Philosophy. It inherited the Classical world to open it to the perspective of the Modern one within the discoveries of the XX century. Thus, its teaching could be a strong opportunity in enhancing the development of students' learning process as it links different field of knowledge, thus activating different aspects of reasoning.

For many years, high schools have been trying to keep up with the new discoveries of Modern Physics, making it necessary to introduce the main topics of Special Relativity within the Physics curriculum. From students' point of view, this implies starting to deal with new aspects of reality far from their everyday life and contrary to their sensitive experience. In this context it needs to be explored how Special Relativity is taught in high schools and the difficulties students face while studying this theory. Indeed, an incomplete process of assimilation risks ending up with a product of Einsteinian concepts with Newtonian foundations due to learners' metaphysical commitments to Classical Physics [2; 4-5]. Students, in order to preserve the previous knowledge of Classical Mechanics, create ingenious solutions or invent personal scenarios where the classical quantities are maintained (as simultaneity for instance) despite the concreteness of the situation they depict [4; 6]. Thus, the misunderstanding of the structure of Classical Mechanics is a huge obstacle to the comprehension of Special Relativity [7].

Different researches pointed out students' alternative frameworks about Classical Mechanics while Aslanides [8], Alstein *et al.* [9] and Prado *et al.* [10] reviewed students' difficulties and alternative frameworks in Special Relativity as well as the strategies and approaches to its teaching. A completed summary of these works has been reported in the PhD thesis of the main author of this paper [11] and in another Master Thesis [3].

When we consider Classical Mechanics [12], researches show that students' problems are related to the concept of reference frame [7; 9; 13-14] which is not held by students [7] but it is necessary for a correct and global understanding of Special Relativity [5; 7; 13]. Students have difficulties to determine what makes a reference frame [15]. As we described [11], Galilean Relativity is affected by students' intuitive kinematic ideas and the principle of Galilean Relativity is not used as a powerful tool to determine answers to different problems. Instead, it is considered only as another law to be memorised and its violation is rarely recognised.

These difficulties influence the understanding of Special Relativity, in the aspect of the principles of Relativity, simultaneity, causality, time dilation, length contraction and mass-energy equivalence. To face the impossibility of experimenting with relativistic phenomena, students appeal to their common sensory experience [4] with a negative impact on the reasoning process. Students tend to adopt the ground reference frame [4; 9; 14; 16–19] as the preferred one with an absolute sense. The misconception [14] between a real and an apparent motion is even more emphasised leading students to consider time dilation and length contraction as an optical illusion [1-2; 4; 16; 18] as well as asymmetric phenomena [8].

Different solutions are being proposed to effectively teach Special Relativity in high schools: as we already reviewed and discussed [11-12], in literature a common consensus over the use of spacetime diagrams was found but this approach is still not widely diffused. Prado *et al.* [10] clearly points out that "the literature shows that using spacetime diagrams is an efficient procedure to answer and explain questions, dilemmas and paradoxes of the theory".

We used these global results to carry out a doctoral study between 2019 and 2022 with the Department of Mathematics and Physics of Roma Tre University in Rome [11] with a project on the teaching of Special Relativity by the means of the spacetime globe [11-12, 20] and in this contribution we are going to summarise some evidence we observed about students' misconception on both Classical Mechanic and Special Relativity.

2. Spacetime globe

The spacetime globe (figure 1) is a new tool in the landscape of the didactic of Special Relativity [11, 21] which allows the construction of interactive Minkowski bi-dimensional spacetime diagrams.

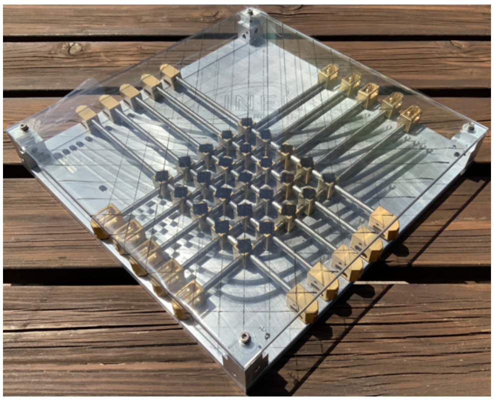

Figure 1. Our spacetime globe.

This instrument is actually a spacetime diagram where the time axis *ct* and the spatial axis *x* are shown on the grid and events in spacetime are represented by each one of the underlying dice. The peculiar feature of this tool lies in the possibility of moving these elements along the hyperbolas-shaped tracks engraved over the base, acting manually on the handles at the far end of the bars.

The fundamental idea of this instrument is simple: relativistic effects arise when a given phenomenon is observed and measured from two different observers in relative motion. We can now use a reference frame to depict our observers. This is a critical step as Panse *et al.* [22] and Scherr *et al.* [13] showed; we need to be careful as students tend to identify single observers with single different reference frames while instead a reference system describes a class of observers, namely the ones at relative rest.

In a spacetime diagram, an observer is represented by a worldline and we can figure all the relativistic scenarios simply starting from the worldlines of different observers in uniformly relative motion. The effort of changing the perspective from one observer to another one can be easily achieved shifting the worldlines as shown in figure 2.

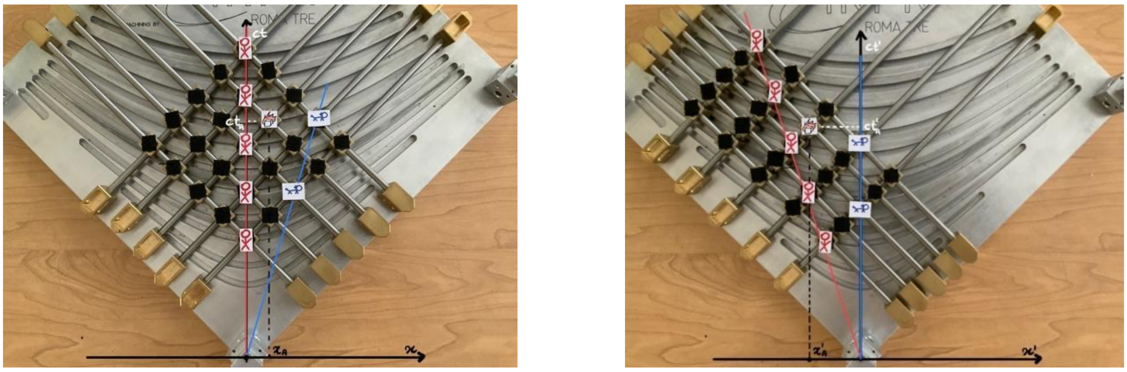

Figure 2(a). Red man's point of view. **Figure 2(b).** Blue cat's point of view.

Figure 2. Transition from the red man's perspective to the blue cat's perspective.

The spacetime globe allows to represent qualitatively and to measure quantitatively all the relativistic effects: we can investigate the loss of simultaneity, time dilation and length contraction, the relativistic addition of velocities, the invariance of light speed and of mass, up to the Doppler effect. Their full and complete description has been reported in our previous works [11; 23].

The strictness and accuracy of this instrument is guaranteed by the hyperbolas tracks which are the geometrical locus of the Lorentz transformations: we showed that each time a reference frame is changed with the spacetime globe, the corresponding Lorentz transformation with the parameters of the depicted scenario is performed [11; 20].

This instrument hides the mathematics of Lorentz transformations inside the complexity of the dynamics mechanism and allows to focus on a more practical and laboratorial aspect while teaching Special Relativity. Learning at different levels can be explored going from a more qualitative to a one more quantitative up to understanding the Physics behind the movement of the dice. Thus, the spacetime globe integrates multiple representations in describing Special Relativity (Maths and formula, spacetime diagrams, event diagrams, experiments) which favours the learning process.

3. Experimentation

Since we were interested in exploring to what extent the spacetime globe by the means of spacetime diagrams could provide a better assimilation of Special Relativity, in s.y. 2020-2021 we planned a project, following the feedback of some high-school teachers interested in our tool [20]. A detailed description of the experimentation has been already presented elsewhere (see for instance [11-12]) and here we are going to summarise its main structure.

We designed our pilot experimentation with two lectures two hours long dealing with the themes of greatest interest from a scholastic point of view. We focused on most of the relativistic effects (loss of simultaneity, time dilation, length contraction, relativistic addition of velocities and invariance of light speed) trying an experimental approach using the spacetime globe.

Indeed, we depicted all the relativistic effects on the spacetime globe by the means of worldlines and spacetime diagrams. We highlighted the connection between a reference frame and the point of view of an observer, replacing the idea of "changing a reference frame" with "adopting a different point of view", similarly yet independently from Gousopoulos *et al.* [24].

Our experimentation involved five different groups attending the last year in three different high schools of Rome. Since four out of these five groups already attended scholastic lessons on Relativity, our experimentation should be considered as an integration. We also structured a prepost to have a first insight on students' knowledge of Classical Physics and of Special Relativity, trying to understand if our intervention had favoured the assimilation of the latter contents. We did not investigate explicitly the understanding of the geometrical properties of the contents of our lessons since our aim was mainly addressed towards Special Relativity rather than Minkowski's geometry.

The pre-test was given at the beginning of the first lecture; it is organised with seven multiple-choice questions and five open-questions about Classical Mechanics concepts and Galilean Relativity. The post-test was given at the end of the second lecture; it is organised with nine multiple-choice questions and four open questions exploring the Special Relativity concepts faced during the lectures. The total number of the answers to the pre-test were 95 with respect to the 85 answers to the post-test, with 77 individuals taking both tests.

4. Results

We already reported the full statistical analysis of the answers to the multiple-choice questions to both the tests in another work [12]. Here we give the full description of students' answers to the open questions (see https://t.ly/Uf-rJ); our study seeks to address the following research question:

[RQ] What are the students' frameworks regarding reference frames and relativistic effects?

Students' responses were thematically coded to identify common trends and ideas, as well as discrepancies in their views, according to three epistemological profiles - everyday, meta-scientific and scientific answer [11]:

- everyday: this kind of answer reflects the creation of situational meanings derived from everyday contexts or common knowledges and sense;
- meta-scientific: the student does not explain the causal relationships between the involved parameters on the basis of a functioning model (microscopic/macroscopic). He merges common sense to some scientific notions taken from scientific context (lectures, books, mass media...). Thus spontaneous schemes are framed into scholastic reasoning;
- scientific: the student proposes a model (qualitative and/or quantitative) based on a cause/effect relationship or provides explanatory hypotheses introducing models that can be visualised at a theoretical level.

These three different strategies of answering correspond to three different levels of capability in dealing with problems. This kind of analysis allows us to distinguish between common knowledge and scientific knowledge [25] plus meta-scientific knowledge.

4.1. Pre-test

The pre-test has five open-questions. All the students answered the pre-test but for each question we excluded from our analysis some answers corresponding to not given or meaningless ones.

4.1.1. Question 2: absolute motion. This question asked to motivate whether it was possible or not to be aware of one's own state of motion being inside a moving car with no glasses.

Most of the students (~66%) gave common answers related to sensory experience (seeing, hearing, perceiving); we can gather them into four different groups:

- The ~30% of the answers concern the possibility of perceiving the motion through acceleration or the presence/absence of some kind of movement within the car. This group lacks a cause/effect relationship between acceleration and the motion inside a non-inertial reference frame, namely the chain acceleration-fictitious force-movement. Students' answers show that they ascribe the main source of detection of the car's state of motion directly to the (non-inertial) motion within the car, without mentioning inertial acceleration. Furthermore, this reasoning is not related in any way to the principle of inertia.

- The ~21% of the answers simply state that as they are not able to see outside, it is impossible to be aware of the car's state of motion.
- The ~30% of this group is a sort of evolution of the previous one: yet students are not able to detect the motion because of the absence of glasses inside the car but they explicitly wrote about the lack of external points of reference. This detail is a precursory notion of reference frame.
- The ~19% of the answers refers to some kind of "reference frame" (external or internal), even if this idea is not always used appropriately. Either they think of not having a reference frame or, as they move within a reference frame, they do not perceive the motion.

Another ~23% of the students gave an answer that still has some features related to common sense but also some scientific aspects. The detection depends upon the state of motion of the car, namely if its motion is accelerated or not, and the sensory effect upon the body. Two students thought to perform an experiment but these answers lack some more details as for instance that if the car was moving with constant speed, even an experiment would have given no result. One student just used the principle of inertia without giving a real explanation about it and finally another answer is related (in some not clear way) to Mach's principle. This item is particular as the student wrote "There are not points of reference (Mach's principle)". This lets us think that also the previous common answers about the absence of points of reference could be related to students' understanding of Mach's principle (3 groups of students over our examined sample did deal with Mach's principle in their lessons).

Finally, a ~11% of the students showed some kind of scientific reasoning: they distinguished between an accelerating car or not, some of them explaining the effect of acceleration in terms of forces. Indeed, these answers do not differ a lot with respect to the previous ones (meta-scientific) but we chose to classify them as scientific because of their use of a more appropriate vocabulary and because they gave more precise explanations.

4.1.2. Question 5: addition of velocities in Classical Mechanics. Students were asked to explain why when one is in a moving train and another train passes near him at the same speed but in the opposite direction, it seems to have a higher speed.

Most of the students (~71%) gave a common answer that can be expressed as simply "Speeds are summed" (or doubled). A little part of them (~39%) also specified that this is due to the fact that the two trains are moving in opposite directions.

As far as the meta-scientific answers are concerned (~29%), we can identify different aspects: the greater part of them (~71%) referred to the presence of reference frames, while other 3 students thought in terms of vector addition of velocities; one student cited the Dialogue Concerning the Two Chief World Systems (maybe remembering Galilean Relativity) while the last one referred to the presence of relative motion. Finally, the other two answers correctly identified in the composition of velocities the origin of this phenomenon and the subsequent sum of their modules.

No truly scientific answers were found among these replies as, regardless of the kind of the given answers, there is the general tendency to treat this phenomenon as apparent. Indeed the ~52% used expressions as *it seems*, *I see,* and *it appears*. One student explicitly wrote "one gets the illusion that" while another one wrote that the doubling of the speed "is not true".

4.1.3. Question 6: apparent motion in inertial reference frame. Students were asked to explain what we can learn about relative and absolute motion from the experience of misunderstanding whether it is our train which is departing or the one next to us.

The common sense answers (∼26%) involve explicitly the dependence of the motion on one's eyes (they are used to follow a moving object) as well as the impossibility of detecting the motion and a change in the perception of time and of the spatial coordinates. Finally, a consistent group of students (the half of them) answered in a very common way: "it is a matter of relativity".

Meta-scientific answers (∼72%) show that students well understood that there is something observer-dependent. We can identify some clusters:

- Students referring to the perception and observation of the observer-dependent motion.
- Students referring to the motion which is observer-dependent.
- Students invoicing Mach's principle to use a third frame to establish who is really moving.

One answer is scientific: it well contextualises the phenomenon, using appropriate words.

4.1.4. Question 9: physical law in inertial reference frame. Students were asked to explain if the time taken for an object to fall inside a moving train is the same as measured from outside.

One half of the answers are common sense, related to air resistance, intuition, or a general sentence as "time does not change", actually not replying to the question. A consistent part of the common sense answers (nearly ∼51%) are linked to the concept of velocity: independently from the given answer, they ascribed it to the fact that the speed of the falling object is summed to the one of the train.

Among the meta-scientific answers (∼47%) we can find references (∼33%) to time dilation with a clear misunderstanding of the question. We can find another group (∼15%) similar to this one mentioning Special Relativity but they contextualised the answers: the time interval is the same, even if there is a small variation according to Special Relativity that could have had a higher effect if the train would have moved faster. Then another cluster (∼27%) again answered that time is invariant but they detailed more with a scientific-like language. The last group (∼24%) agreed that time is greater as the trajectory is wider due to the movement of the train from the external point of view. The lying misconception that in projectile-motion the time of falling depends on the *x*-motion is present in this group as well as in the common sense answers.

Finally, we identified two scientific answers (∼3%) that correctly linked the time of falling to the vertical motion which is determined by the gravitational acceleration and is not influenced by the speed of the train. However, it lacks the general frame of time invariance in Classical Mechanics.

4.1.5. Question 12: accelerating indefinitely. Students were asked to comment whether it is possible or not, being $v = at$, waiting for as much time as required, to reach each desired speed with a car equipped with a very performing engine.

Between the common answers we identified two groups equally distributed:

- The ∼53% of the answers reported that the correctness or not of the question depended on the limits of the engine itself.
- The ∼47% of the answers reported that the question was true/wrong due to the absence/presence of friction. One reply identified that air friction increases with speed, a more scholastic feature.

The remaining answers (∼64%) are all meta-scientific. They are more or less equally divided into two major groups and another small one:

- The first group of items (∼49%) replied that the reasoning is wrong due to the existence of a limit speed, namely the light's one. Most of the answers seems to be truly scholastic: it would be interesting to investigate whether this conception is actually already known before instruction in order to understand if it is a common knowledge.
- The second group of items (∼40%) replied that, according to the formula $v = at$, the reasoning is correct, being the speed proportional to time and to a constant acceleration. There is an interesting answer among the other: "Actually, the speed of light cannot be exceeded but if the car has an infinitely powerful engine, I can say that it can also exceed it". It can be considered a prototype of this kind of answer: students seemed to consider the law as a kind of

truth, not actually questioning it in relation to the real world. Nevertheless, it shows a correct understanding of the formula.

- The last ~11% replied that, being the car a massive body, it cannot reach the speed of light.

It was not possible to find a complete scientific answer: no one contextualised the replay into the Classical Mechanics frame. Actually, some items inside the second group of meta-scientific have a more appropriate scientific language but a complete answer should include both the reasoning on the inertia effect of the acceleration and the consequent energy supply for the car.

4.2. Post-test

The post-test contains two open-questions about time dilation and two about length contraction. As for the pre-test, we excluded from our analysis some answers corresponding to not given or meaningless ones or copied from the Internet.

4.2.1. Question 3: how would you summarise the time dilation phenomenon? More than one half of the students (~61%) gave common answers and we can distinguish different alternative thoughts:

- The ~19% of them simply stated that "the greater is the speed, the slower the time flows" which can be regarded as a very popular way to summarise Special Relativity.
- The ~44% of them stated that time depends on the reference frame, which is very similar to the previous one, but the answers contain an additional element, namely the reference frames. However, there is not any statement whether they are moving or at rest. It seems to be an intrinsic property of the reference frames.
- The ~33% of them looked to time dilation as an intrinsic property of the moving reference frame, thus stating that time gets dilated only according to the moving observer.

We also noticed that one student among the previous ones referred to human perception of time as changing (*time's perception changes* [...]), perhaps forgetting to consider that physical time can be only measured. Another one alluded to time dilation as an apparent phenomenon, depending on the reference frame adopted (*time* [...] *seems to be greater* [...]). One student also mentioned that it is a property of a body to modify time, dilating it: maybe he got confused with General Relativity and with masses' property of bending spacetime. Finally, we report a third answer stating that in different reference frames time can dilate: it is not clear what this chance depends on.

Another ~18% of the total students gave an answer that still has some features related to common sense but also scientific aspects. A half of the students linked time dilation to the principles of Special Relativity (in particular the constancy of light speed), however not really explaining the meaning of the phenomenon itself. Another student started from loss of simultaneity to explain that again time perception is no more universal. Other two students wrote about measuring time and the result one obtains according to different observers but with some vagueness (one of them did not express how it varies while the other referred only to high speed). The last answer is out of these kinds of replies: the student alluded to a difference between local time (maybe the one of the observers we are referring to) and absolute time because of the presence of the term v/c in the Lorentz transformation. Similar to some consideration of Scherr *et al.* [6], it seems that this student tries to justify, actually mixing, his belief with some feature of Special Relativity, revealing that, as outlined in literature, Lorentz transformations are not an operative tool.

Finally, a ~23% of the students showed a scientific reasoning in this question: in each reference system time flows in the same way but when one observer measures the time of the other reference system, he will register a different value. Some of the students highlighted explicitly the need of comparing the measure of the two different reference frames. However, from a linguistic point of view, sometimes students correctly answered but did not express in an Italian good lexical form.

4.2.2. Question 5: can we perceive the time dilation phenomenon? This item is related to another question where students have to say if it is true or not that being aboard a moving train one can see from his own clock a different value with respect to a clock at rest (question 4 of the post-test). In this question students were asked to explain why the previous one was true or false.

A small part (~11%) of the considered answers replied in a common way, stating correctly that it was false as time flows equally. As we already discussed [11], linking their answer with the one to the previous question (question 4 of the post-test), it may not be considerable to infer a correct understanding of time dilation phenomenon. Indeed, some of these students still referred to the perception of time as changing while the measurement of it would remain the same.

The greatest part of the answers is meta-scientific and we can identify two kinds of reasoning:

- About ~60% of these students clearly did not understand the phenomenon: relating the answers to different intertwined questions, it emerges that these students believe that time dilation is a local phenomenon, namely it is a property of the reference frame. They ascribe the truthfulness of the awareness of time flowing slowly to time dilation phenomenon itself: thus being aboard a moving train one can perceive time dilation without taking into account the relativity principle. The answers to all these three questions show a consistency and coherency into students' reasoning, even though not scientific.
- The other ~40% correctly replied that it is not possible to perceive time dilation phenomenon; their explanations refer to the idea that there is not a change of reference frame or equivalently the observer is always in the same reference frame. It seems to be a sort of learnt statement, a kind of "magic formula" that can be used in relativistic situations.

Finally, the remaining 10% of the students showed a scientific reasoning: they stressed the relativity nature of time dilation stating that the time difference arises only from the comparison between clocks of different reference frames. In only one answer there is a kind of reference to the covariance principle asserting that in every inertial frame the measure of a physics event must give the same result. Even if there is a confusion with the meaning of event as a full correct answer should have involved a mention of the result of an experiment, not a measure of an event, this is the only answer referring to the relativity principle.

4.2.3. Question 7: how would you summarise the length contraction phenomenon? The common sense answers (~29%), as one could expect, summarised length contraction as "the greater the speed, the shorter is the length of a moving object". This assertion has different declination according to what gets contracted. Indeed, students referred to length or lengths, space or spaces and also to the moving body itself. Similarly to time dilation, length contraction seems to be an intrinsic property of the reference frame: a half of these students stated that the phenomenon depends on whether a reference frame is moving or not. Indeed, we noticed the students used verbs as *it is*, *it becomes*, *it results contracted* as if the phenomenon is a property to be ascribed to the body or to the reference frame.

We noticed also that the common answers are the half of ones of question 3 (section 4.2.1) while the meaningless answers and the one copied from the Internet increased: we could infer that perhaps there is a link with a less common knowledge of this phenomenon.

The number of the meta-scientific answers (~51%) also increased with respect to the ones of question 3. We can distinguish different addresses for these replies:

- The ~14% of students used Lorentz transformations as an explanation of the phenomenon.
- The ~29% of students referred to the visible effect of rotation for a body moving at high speed (Lampa-Terrell-Penrose effect), perhaps getting confused by it. They used verbs as *to see*, *to be*, *to appear*, thus perceiving the phenomenon as an illusion (as someone wrote) due to this rotation. However not all the groups knew about Penrose rotation.
- The remaining 57% of students referred their answer again to a visual phenomenon, not linked to the previous rotation. They simply stated that an observer in relative motion with respect to an object will see it contracted, shorter than if it was at rest. They tended to use the same verbs as the students of the previous grouping.

The remaining ∼20% of the answers can be addressed as scientific ones and focuses over different measurements of a length in two different reference frames in relative motion, even though without explaining the measure's process and in which direction the length gets contracted.

Finally, as a check of the given answers, we compared these replies with the ones to question 11 in which, similarly to fourth, we asked if being aboard a train moving at high speed, we would have seen the length of the carriage contracted. We found that ~66% of students correctly replied to this question and that almost all the incorrect answers were given by the students who did not answer this seventh question or copied from the Internet. This is to infer that maybe ∼66% of students grasp the relative feature of length contraction phenomenon.

4.2.4. Question 9: explain the result of an exercise over length contraction. This item is related to the eighth question where students had to indicate the length of a table in a moving train according to an external observer between L, γL and L/γ, being L the proper length.

For this question, we excluded more or less a half of the answers (∼44%) corresponding to students that, regardless of whether they answered the previous question correctly (∼36%) or not (∼64%), are not able to motivate their choice. This may point out a not full understanding of the phenomenon.

Among the answers, there are only two common sense ones stating that inside the moving reference frame (the train) length is shortened.

All the other (∼96%) are meta-scientific ones and we can identify different groups of answers:

- The ∼24% of the answers showed an internal contradiction: students chose an incorrect answer to question 8 (according to the external observer, length is dilated $L' = \gamma L$) but they motivated this with length contraction. Maybe students got confused with the formulae.
- Another ∼33% chose the correct answer to question 8, motivating it simply "because of length contraction". Moreover two students stated that the measured length is shortened with respect to *real* one, thus implicitly inferring the existence of a privileged reference frame.
- The ∼17% of students used mathematical reasoning: being the length contracted, the only possible answer is $L' = L/\gamma$ as in this way $L' < L$.
- Two students answered correctly to question 8, arguing that the two extremities of the table occupy two different spatial positions (they used improperly the word *space*) and thus the light coming from them would reach the external observer in two different instants of time.
- The last ∼22% of students referred to the presence of motion, stressing different features, never however writing a complete reasoning: the 40% of them stated that there is a motion while another 40% added that the measured length is along the direction of the speed. The last 20% of them indicated that L/γ is the correct formula as it prevents from considering the two extremities of the table at different instants of time, thus not measuring two simultaneous events. They are the only answers referring in the same way to the requirement of measuring distances as differences of spatial coordinates taken at the same instant of time.

5. Conclusions

The analysis we carried out revealed the presence of alternative frames in students' reasoning on Classical Mechanics and Special Relativity, confirming the previous outcomes in literature [8-10].

We noticed that students firmly rely upon sensorial experience which constitutes the base of their reasoning: Physics phenomena are investigated through sensations they can experience (the lack of the effects of non-inertial forces) rather than on scientific principles. They do prefer to use a common or dynamical explanation rather than a law and this agrees with the research of Ramadas *et al.* [17], stressing that Galilean principle is just a "cliche" to remember. The concept of reference frame is not still completely assimilated as it is considered depending on the observer. Especially from question 5 and 7 of the pre-test, we noticed the tendency of regarding as apparent the phenomena occurring in moving reference frames that infers implicitly the presence of a privileged reference frame. A quarter of the students believes in the existence of an absolute reference frame and this is particularly evident as far as Galilean addition of velocities is concerned. Indeed, it is considered as an illusion due to the presence of a "real" reference frame with respect to which the "real" speed can be evaluated. As Panse *et al.* [22] observed, this is a recurring misconception about reference frames.

Even if we look at the phenomenology of Special Relativity, we can notice students' strong belief in the existence of an absolute reference frame: time dilation and length contraction are *asymmetrical phenomena*, happening only in the "moving" reference frame as already Aslanides [8] pointed out. The principle of relativity and its consequences is not used as an operational tool to reason about relativistic phenomena. In a very common way, students think of these phenomena as "the greater is the speed, the slower the time flows" and "the greater the speed, the shorter is the length of a moving object". Finally, the presence of sensorial experience is shown in students' reference to time dilation as a human perception (time's perception changes) and to the possibility of seeing a contracted object, not measuring a contracted length, a confusion Panse *et al.* [22] already found in Classical Mechanics.

Thus, our analysis reveals a not-complete understanding of Galilean Relativity and of some fundamental concepts of Classical Mechanics (as the one of reference frame), conditioning the meaning of Special Relativity. The existence of an absolute reference frame leads to an asymmetric feature of relativistic phenomena [4]. The sensory experience still plays a key role in students' reasoning and the strong commitment to the mechanistic view of reality is revealed in their thinking of the bodies as having rigid, fixed length [2].

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