A fine-grained teaching activity to establish conceptual coherence in introductory physics concepts and representations

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Abstract. The sequence of representations used to introduce new knowledge and the context in which this is done is critical to both effectively build on prior knowledge and establish conceptual coherence in physics. Ongoing reports indicate that current teaching activities fail address student difficulties to obtain conceptual understanding and coherence between relevant physics representations and concepts. There is a need for fine-grained topic specific multiple representational teaching activities to enhance coherence in physics knowledge. In this paper we present a teaching activity for undergraduate physics, built on using motion diagrams to specifically relate the concepts and representations in kinematics, in particular for the concept of free fall. The teaching activity follows a conceptual qualitative approach to teaching kinematics concepts and is informed by the results of a broader Design Based Research study. In the teaching activity the concept of acceleration is introduced qualitatively as the net force to mass ratio followed by drawing motion diagrams to visualize the motion of the objects in free fall. The motion diagrams are implemented to support conceptual qualitative interpretation of mathematical representations such as graphs and equations, to enhance transfer of knowledge between representations and coherence between relevant concepts and representations. The contribution of this research lies in presenting an argument for a conceptual qualitative approach to teaching introductory mechanics and introducing a teaching activity based on the value offered of including motion diagrams in the teaching activity to enhance coherence between physics representations and between physics concepts.

1. Introduction
Many learning theories have one common feature: it is important to identify what students already know before teaching them \cite{1,2,3}. Since learning is a process of knowledge construction undertaken by an individual, new knowledge is elaborated and/or reconstructed from this basis \cite{4}. The importance of the situation in which the knowledge is introduced is emphasized because relations between prior and new knowledge elements are constructed according to student’s “overall understanding of the situation” \cite{5}. The lack of perceived coherence of the structure of physics knowledge is among the principal causes of student failure to achieve conceptual understanding in physics \cite{6}. There is a need for well-developed, content-oriented teaching sequences paying particular attention to the learning and teaching of specific disciplinary content, i.e. fine-grained teaching sequences aimed towards teaching a very specific topic. This paper presents a conceptual qualitative approach towards the design of teaching (and learning) activities to assist the transfer of information between physical and mathematical representations of...
kinematics, thereby enhancing conceptual coherence between relevant concepts and representations of motion.

Despite the acknowledged and profound deficits in learning resulting from traditional teaching, adoption of the few successful research-based instructional approaches and strategies in the subject of physics remains low. While various researchers have, for example, investigated and reported on learning progressions for different physics topics to develop conceptual understanding of physics principles [3][6][7] there is a lack of teaching approaches and strategies that use student intuitive knowledge as anchors to bring about conceptual change and to develop or enhance conceptual understanding of specific fundamental concepts.

In this paper the focus is on a conceptual qualitative approach to linear kinematics, particularly the concept of free fall. This approach has particular and specific emphasis on the use of motion diagrams to relate (a) the concepts and relationships central to explaining free fall and (b) other modes of representation of these concepts and relationships. Changes in displacement and velocity during specific time intervals are related to the fundamental concept of acceleration. The concept of acceleration is presented from a qualitative perspective as opposed to the usual mathematical approach as the time derivative of the change in velocity. We present the changes in displacement and velocity from a conceptual qualitative angle, as the effect or result of acceleration. A constellation (arrangement) of representations [6] in which motion diagrams are extensively used to relate the different physics concepts involved in free fall motion in a specific sequence, was identified, compiled, and are presented here.

Motion diagrams enable visualizing objects’ accelerated motion and link the motion to different variables, for example, acceleration, velocity, and displacement/distance travelled, and to other representations of the same motion, e.g. physics equations or graphs. This fine-grained constellation of representations, of which motion diagrams seemed to be a critical representation, intentionally chosen and sequenced for the specific topic, was intended to develop qualitative mathematical reasoning and enhance coherence of relationships between different physics concepts and representations, and indeed succeeded in this goal.

The detailed research question formulated to guide the design and evaluation of the fine-grained teaching sequence was: To what extent does the inclusion of motion diagrams in a constellation of multiple representations contribute to student understanding of the conceptual relationships between the physics variables and representations for free fall motion?

The teaching activity aims to aid qualitative mathematical reasoning and to enhance coherence across physics concepts by relating the affordances of multiple representations through implementation of motion diagrams.

In section 2 below, we discuss some theoretical aspects underpinning this research.

2. Theoretical aspects
The development of a deep understanding of fundamental relationships and core concepts in kinematics, and mechanics more generally, remains challenging. Many studies have reported that student conceptual development is related to both their cognitive understanding of individual physics concepts and their epistemological beliefs about physics [8][9][10]. It is only recently that an increasingly stronger focus on the design and implementation of detailed teaching-learning sequences that focus on the improvement of student understanding can be seen [3][4][7][10][11]. A review of the literature revealed three interrelated theoretical areas: student beliefs about the nature of physics knowledge and the extent of coherence of physics concepts, modelling of real-world situations into physics situations, and coherence of physics representations to assist in conceptual change and enhancing the relationship between physics and mathematics. These areas are central to the development of fine-grained teaching activities and are described in the section below.
2.1. Building on existing knowledge
Some students believe that physics knowledge consists of isolated individual facts that are irrefutable and if those facts are in contrast with their experience, they perceive physics knowledge as a set of incoherent unrelated constructs [3]. For example, the term ‘free fall’ implies that gravity is the only force acting on the falling object, i.e. air resistance is absent, resulting in all falling objects having equal acceleration. This does not concur with student experience that ‘heavier objects fall faster’ resulting in an alternative conception which is not scientifically true. Students construct their ideas and observations based on what they already know and believe, therefore student beliefs regarding physics knowledge are central to the documented difficulty of creating student conceptual change [3][12][13]). Since the ways of making sense of one’s world in order to control it are central to the nature of pre-instruction alternative conceptions in the domain of mechanics alternative conceptions may already be well integrated for many students before instruction.

Alternative conceptions that are not challenged become integrated into student cognitive structures [14]. By reformulating common physics questions, for example by changing the direction/plane of motion or the variable to be solved for, the existence of the alternative conception that heavier objects fall faster in free fall can be identified. Such reformulated questions can also indicate the level of student understanding of the new concepts/content that are introduced [15]. It is argued that to address student alternative conceptions, a multiple conceptual change view that includes conceptual changes on the fundamental level of concepts and principles is required [10]. The view of building on existing conceptions means that instead of expecting the students to replace their conceptions on the basis of being told to do so, acceptable scientific conceptions are developed by acknowledging and revising student’s alternative conceptions [3][17]. However, to revise student alternative conceptions, it is vital that students are made aware of the conditions that lead to the formation such alternative conceptions [15].

2.2. Modelling of real-world situations into physics situations
Real-world phenomena are influenced by multiple and complex variables which require advanced physics for prediction and mathematics for measurement of those phenomena. The mathematization of physical systems not only involves transfer of mathematical techniques to the physical environment, but also the merging of mathematical symbols and reasoning with physical meaning [18]. Many teachers assume that because it is easy to teach physics mathematically, it is also easy to learn physics mathematically. However, that is not the case [19]. Introductory physics knowledge to be taught is often manipulated for physics teaching by deliberately ignoring some disciplinary aspects. When introducing principles underlying real-world phenomena to high school or undergraduate students, these real-world phenomena are simplified by disregarding factors that are distracting in terms of the underlying physics principles to be learned [10]. Everyday situations are often modelled into theoretical physics situations by simplification, for example, by ignoring the effect of air resistance for falling bodies. The problem is that students are seldom given any measures and ways of judging what to disregard and what not. As a result, simplification of everyday situations often contributes to student difficulties to apply physics knowledge to their daily life. [15]. Although research has reported on unintentional difficulties caused by such modelling, clarification of when such simplification would be justified or not has only recently been addressed [16].

2.3. Teaching specific disciplinary content.
Specific detailed knowledge about the teaching and learning of specific content – knowledge at a finer grain size – is needed to enhance student understanding [11]. Thebulk of research on the teaching and learning of physics in particular, can be described as being at a large grain size, with investigations of process or practice being considered in terms of broad physics content [11]. Although these general large grain sized insights around teaching and learning physics are valuable, many fine-grained sized decisions, both about content and pedagogy, in designing teaching sequences for topic specific disciplinary content need to be made [20].
Furthermore, it is important to know which concepts are considered threshold concepts for specific content matter and to include representations that would maximise understanding of those concepts (such as acceleration) in suitable teaching activities. For example, a good understanding of the force-mass-acceleration relationship as it applies to objects moving in a gravitational field is critical in providing a foundation for student knowledge of other physics concepts, such as the laws of conservation of energy and momentum, and projectile motion [21].

Meaningful physics learning requires fluency in applying various modes of representations. Understanding the qualitative non-numeric connections, of variable represented in physics equations and other aspects of the physical situation, are critical in developing understanding of the relationships between physics quantities [22]. If precise calculation is considered more important than the ability to interpret equations qualitatively, the use of physics equations and other mathematical representations such as graphs, as reasoning tools remain hidden from students [23].

Justification for the use of multiple representations is found in the dual-processing theory [24]. According to the theory, the human brain has separate processing systems for verbal and visual input that can be used simultaneously. As a result, more can be learned from words and pictures than from words alone [24]. As each representation has a unique set of affordances the use of multiple representations means the representations complement each other, and a carefully designed constellation of representations provides teachers with valuable instructional affordances [25]. For example, motion diagrams are a standard form of pedagogical representation used in mechanics. In a motion diagram the object’s position throughout the motion is recorded at regular time intervals (with this being shown as sequential dots on a paper strip as if being created by a ticker timer). By comparing the distance between consecutive records (e.g. dots on ticker tape), the objects’ displacements, velocities and accelerations can be compared visually. Teachers should understand which representation/s to choose for a specific task, depending on the properties of the information to be presented, the material to be understood and the meaning-making potentials of the representations. To make such a choice requires knowledge of the affordance attributes of each possible representation of given material, as well as the contribution of each representation to the collective disciplinary affordance.

3. Research Design

We present a fine-grained teaching activity designed to establish conceptual coherence between physics concepts and representations regarding free fall. The teaching activity is the result of two iterations of an extended Design-Based Research study which primarily focused on knowledge-using as opposed to knowledge development. The results of each iteration were interpreted and further developed and refined for implication in sequential iterations, each with a different set of participants, data collection and analysis strategy. Qualitative data obtained from the first iteration informed the second iteration where we collected quantitative data by means of a pre-post-questionnaire. The commonalities of the iterations were a conceptual qualitative approach to acceleration as the net force to mass ratio and the use of motion diagrams to link the changes in the physics quantities in accelerated motion to relevant kinematic equations.

3.1. Method

In both iterations the students completed a pre-instruction assignment/questionnaire. At the first part of the teaching activity we introduced a conceptual approach to acceleration as the net force to mass ratio – presented in 3.3.1. This introduction was followed by drawing motion diagrams to visualise the motion. In this present research, the concept of equal acceleration of two moving objects was clarified by comparing their motion diagrams. The motion diagrams were intended to enhance student conceptual understanding by enabling a visualizing of the objects’ motion and the linking of the motion and the different variables that can be inferred from the motion diagram, for example, acceleration, velocity and displacement, to other representations of the same motion e.g. physics equations or graphs.
The motion diagrams of two falling objects in two different examples were then compared:

1. In the first example the information motion diagrams offer on the changes in the displacement, and by inference also in velocity of two falling objects, was linked to the applicable variables in relevant kinematics equations which described the same motion.

2. In the second example the information obtained from the motion diagrams, the equations describing the motion were linked to velocity-time graphs representing the falling motion. The qualitative results of the first iteration informed the second iteration where the teaching activity was in part repeated with a large group of students in a quantitative study. The different cohorts of participants and the different sections implemented with the groups are described in the section on data collection below.

3.2. Data collection

The research sample for the first of the two iterations consisted of six in-service Physical Sciences teachers enrolled part-time for a BEd honours Physical Sciences module. The content of the module focused on refining and enriching teaching of the content stipulated in the curriculum for secondary schools in the country. In section 4.1. we present one student’s pre- and post-instruction solutions and answers to the example problems as an example of the development in the students’ understanding of the relationship between the different representations and concepts of free fall. The students’ answers showed notable advances in their interpretation of mathematical representations of i) equations and ii) graphs after implementation of the teaching activity. The use of motion diagrams to compare the objects’ motion in a qualitative way seemed help the students to relate the applicable changes in the physics quantities indicated on the motion diagrams, to the variables in physics equations. In the second part of the iteration (example two) the relationship between representations was extended to include graphs describing the motion. The results of this exercise indicate that the students’ ability to interpret and analyse graphical representation also improved post-instruction.

The promising results of the first iteration informed the second iteration of the activity. The aim was to obtain quantitative data to evaluate the practical significance of the teaching activity. The participants in the second iteration of the teaching activity were 297 undergraduate first-year physics students. To align the teaching activity with the curriculum for this physics module only the first part of the teaching activity (linking motion diagrams to equations) was used.

For the quantitative study, the pre-test questionnaire contained nine variations of the question in example one. In all the questions the motion of two free falling objects of different mass were compared. The context of each of the questions differed from the others in terms of the direction of motion of the two objects or the variable to be compared. For example, in some questions the objects were moving either vertically upward or downward, in other questions the motion was up- or downward along an inclined plane. In some questions the velocities were compared while in others the distance travelled/height reached, or the time were compared. Each question contained an option that would indicate the existence of the alternative conception that heavier objects fall faster. Such an option was included to get an indication of the effect of the conceptual approach of acceleration in the first part of the teaching activity. The post-instruction data were obtained from a test in which four of the pre-instruction questions were included. The test was written three weeks after the teaching activity. The results of the questions in both the pre- and post-tests were compared to evaluate the effectiveness of the teaching activity.

3.3. Sequence and representations used in teaching activity

3.3.1 Acceleration as the net force to mass ratio.

Consider two balls of the same size but different mass e.g. a shot put and a rubber ball. The shot put is more massive than the rubber ball - 30 times as much. If the mass of the rubber ball is m, the mass of the shot put will be 30m. The ratio: \( \frac{\text{how much force is pulling or pushing}}{\text{how much stuff is being pushed or pulled}} \) determines how an object
will accelerate, therefore the force needed to accelerate the shot put to the same extent as the rubber ball will be 30 times as big as the force on the rubber ball.

If the force of gravity is the only force acting on the objects, then the ratio: \( \frac{\text{net pulling force}}{m} \) for the rubber ball and the shot put respectively is:

\[
\begin{align*}
\alpha_{\text{rubber}} &= \frac{F}{m} \\
\alpha_{\text{shot put}} &= \frac{30F}{30m}
\end{align*}
\]

\( \alpha \) all objects subjected to only the force of gravity have the same acceleration. \( \alpha_g = \frac{F_g}{m} \) [26]

Implementation of motion diagrams.

Figures 1 and 2 show the diagrammatic representations for both the problems in the examples used in the first iteration. The questions in the two examples below and variations on these question as described in the second paragraph of the Data collection section were used in the pre-post-test questions of the second iteration.

Example 1: Coherence across diagrammatic and mathematical representations.

Consider two metal balls of the same sizes dropped simultaneously from different heights. The mass of ball B is double the mass of ball A. [Ball A (mass = m), ball B (mass = 2m)]. B falls twice the distance of A to the ground. Ignore the effect of air resistance (as has been done in the motion diagram below). Which ball will reach the ground first?

**Figure 1.** Diagrammatic representation of the balls’ initial positions

**Figure 2.** Motion diagrams included to indicate the balls’ relative positions

Formal representation of variables:

| Physics quantities | \( y \)   | \( v_t \) | \( a \) | \( \Delta t \) |
|---------------------|-----------|-----------|--------|--------------|
| Ball A              | \( y \) (h) | 0         | \( g \) | ?            |
| Ball B              | 2\( y \) (2h) | 0         | \( g \) | ?            |
Formalising the difference in falling time as indicated by the motion diagrams:

**Ball A**

\[ y = v_i \Delta t + \frac{1}{2} g \Delta t_A^2 \]

\[ y = 0 + \frac{1}{2} g \Delta t_A^2 \]

\[ \Delta t_A^2 = \frac{2y}{g} \]

\[ \Delta t_A = \sqrt{\frac{2y}{g}} \]

**Ball B**

\[ 2y = v_i \Delta t + \frac{1}{2} g \Delta t_B^2 \]

\[ 2y = 0 + \frac{1}{2} g \Delta t_B^2 \]

\[ \Delta t_B^2 = \frac{2y^2}{g} \]

\[ \Delta t_B = \sqrt{\frac{2y^2}{g}} \]

Qualitative (non-numeric) transition between representations.

As seen in the motion diagrams, the time for ball B is more than the time for Ball A, but not twice as much. This comparison is formalised in the equations above.

**Example 2: Motion diagrams Introducing qualitative reasoning.**

Two balls A and B (with the same/different mass) are dropped from different heights and at different times. The initial height of ball A is twice that of ball B. Ball A is released first. Ball B is released at the exact moment that ball A passes ball B at height \( h \). Ignore the effect of air resistance. Which ball will reach the ground first? (If air resistance is ignored, the mass has no effect on acceleration because the \( F_g/m \) ratio is the same). See figures 1 and 2 for diagrammatic representations.

Questions guiding reasoning

1. What distance do the balls travel together? (h)
2. What are the initial velocities of the respective balls for that distance?
3. How do the times to cover that distance compare?

| Physics quantities | \( y \) | \( v_i \) | \( a \) | \( \Delta t \) |
|--------------------|--------|--------|----|-----|
| Ball B             |        |        |    |     |
| Ball A             |        |        |    |     |

Qualitative (non-numeric) conceptual reasoning: \( y = v_i \Delta t + \frac{1}{2} a \Delta t^2 \)

For ball B, falling from rest (\( v_{iB} = 0 \),) \( y \) is determined by one term: \( \frac{1}{2} a \Delta t_B^2 \)

For ball A, \( y \) is determined by two terms: \( v_i \Delta t_A + \frac{1}{2} a \Delta t_A^2 \)

But \( y_B = y_A \) therefore \( \frac{1}{2} a \Delta t_B^2 = v_i \Delta t_A + \frac{1}{2} a \Delta t_A^2 \) \( \therefore t_B > t_A \)

Equations - comparative mathematical reasoning: Validation of conceptual reasoning:

**For ball B:**

\[ y = v_{iB} \Delta t_B + \frac{1}{2} a \Delta t_B^2 \]

\[ y = 0 + \frac{1}{2} a \Delta t_B^2 \]

\[ \frac{1}{2} a \Delta t_B^2 = y \]

\[ \Delta t_B^2 = \frac{2y}{a} \]

**For ball A:**

\[ y = v_i \Delta t_A + \frac{1}{2} a \Delta t_A^2 \]

\[ \Delta t_A^2 = \frac{2y - v_i \Delta t_A}{a} \]

\[ \frac{1}{2} a \Delta t_A^2 = y - v_i \Delta t_A \]

\[ \Delta t_A^2 = \frac{2y - (2v_i \Delta t_A)}{a} \]

\( \therefore \) time for B is more than time for A
4. Results and discussion of results

4.1. Results Iteration 1

Student answers on Example 1 problem

![Figure 3. Pre-instruction answer](image1)

![Figure 4. Post-instruction answer](image2)

Student answers on Example 2 problem

![Figure 5. Pre-instruction answer](image3)

![Figure 6. Post-instruction answer](image4)

4.2. Discussion of Iteration 1 results

The pre-instruction answers to the problems were mainly verbalised while in the post-instruction answers equations were included to explain and formalise the relationship between the variables by means of equations (figures 3, 4 and 6). It seems that the motion diagrams were instrumental in helping the student to relate the different variables. The use of a graph (although incorrect) in explaining the solution to problem 2 pre-instruction was insightful (figure 5). The post-instruction answer indicated that including motion diagrams to compare the motion of objects in different contexts, helped the student
to interpret the velocity-time graphs (figure 6) and understand the way the area under the graph indicate the distance travelled. It seemed that the motion diagrams also enhanced understanding the relationship of distances travelled with the objects’ velocity and falling time.

4.3. Results Iteration 2

In table 1 below the data obtained from the pre-and post-instruction questionnaires are presented. The correct responses and the responses indication the alternative conception that heavier objects fall faster are presented as percentages. In tables 1, 2 and 3 the directions of the arrows indicate the directions of motion while the symbol following the arrow indicates the variable to be solved for i.e. $\downarrow v$ indicates the objects’ velocity were compared in downward motion along an inclined plane.

| Correct % | Q3 | Q5 | Q6 | Q9 | Alternative % | Q3 | Q5 | Q6 | Q9 |
|-----------|----|----|----|----|---------------|----|----|----|----|
| $\downarrow v$ | $\downarrow t$ | $\downarrow t$ | $\downarrow F$ | $\downarrow t$ | Pre-test | $\downarrow v$ | $\downarrow t$ | $\downarrow t$ | $\downarrow F$ |
| Pre-test | 29 | 68 | 74 | 70 | Pre-test | 23 | 11 | 11 | 20 |
| Post-test | 9 | 41 | 22 | 45 | Post-test | 51 | 42 | 41 | 37 |

All four pre-instruction questions that were repeated in the post-test (questions 3, 5, 6 and 9) showed both an increase in the percentage of correct answers and a decline in the percentage of students who chose the alternative option, in comparison with pre-test mean scores. These changes are discussed in detail with the results of tables 2 and 3. Figure 7 present these changes visually.

![Correct answers](image)

![Alternative answers](image)

**Figure 7.** Graphical comparison of correct answers and alternative conception in pre-and post-tests

In tables 2 and 3 inferential statistics regarding the changes in the pre-and post-instruction questionnaires are presented. The changes are given in terms of the learning gain/ decrease in alternative conception and the significance of the changes is given in terms of Cohen’s $d$ effect size. The guidelines to interpret the values of the effect sizes are as follows: $d=0.2$ is considered a small effect, 0.5 represents a medium effect while 0.8 represents a large effect [27]. Although effect sizes of $d=0.2$ are statistically significant, the difference is practically trivial. However, larger effect sizes are practically significant. For normalized gain, a value of 0.2 is considered to be the result of normal learning (learning that would occur during normal tuition) but values larger than 0.2 can be ascribed to the intervention that was implemented.
Table 2. Inferential statistics: Normalized gain and Cohen’s d effect size.

| Question | Pre Post | Pre Post | Pre Post | Pre Post |
|----------|---------|---------|---------|---------|
| Context  | 
| % correct | 9 29 | 41 68 | 22 74 | 45 70 |
| % Learning gain | 20 28 | 52 | 26  |
| Normalized gain | 0.2 0.5 | 0.7 | 0.5  |
| Cohen's d (d) | 0.73 0.58 | 1.27 | 0.53  |

Table 3. Inferential statistics: Normalized decline and Cohen’s d effect size for alternative options.

| Alternative option | Pre Post | Pre Post | Pre Post | Pre Post |
|--------------------|---------|---------|---------|---------|
| Question           | Q3 Q9  | Q5 Q10 | Q6 Q11 | Q9 Q12  |
| Context            | 
| %                  | 51 23 | 42 11 | 41 11 | 37 20 |
| Normalized decline | -0.6 -0.5 | -0.5 | -0.3  |
| Cohen's d (d)      | 0.40 0.46 | 0.94 | 0.3  |

The results indicated that the learning gain for all three questions (questions 3, 5 and 6) in the post-test was practically significant, with effect sizes of $d = 0.73$ for question 3, $d = 0.58$ for question 5 and $d = 1.27$ for question 6 respectively. The normalized learning gain for question 9 was 0.50, which is also practically significant as indicated by $d = 0.53$.

All the post-test responses had a normalized gain in correct responses between 0.2 and 0.7, which strongly suggests that the teaching activity have contributed to the students improved performance in the post-test.

The increase in the correct answers on the post-test, presented in table 1, is a result which we ascribed to the teaching activity because of the very specific nature of the questions and the improvements. The graph depicted in Figure 7 shows that for question 6 motion along an inclined plane where time was the physics variable asked the increase in correct answers was the greatest.

The low increase in the correct answers for question 3 ($\Delta v$) may indicate that, despite a better understanding of the concept of acceleration, students were still struggling to relate acceleration to velocity, a variable other than time which is usually the variable to be solved for. This indicates that student difficulties with understanding the velocity-displacement-time relationships with acceleration in different directions of motion (upwards, downwards and at an angle) were not completely eliminated by the net force to mass approach. This issue needs to be investigated in further research stemming from the study.

5. Conclusions

The qualitative results reported on the first iteration strongly indicate the promising contribution of the conceptual qualitative teaching activity to promote students’ qualitative conceptual reasoning and their ability to interpret, and transfer knowledge between different representations particularly to the concept of free fall motion. The qualitative part of the research supported the results of the first iteration where
the effect of the teaching activity was evaluated through detailed comparisons of pre- and post- student performance on kinematics problems.

The teaching activity addresses the issue of student beliefs on the nature of physics knowledge by disputing that physics knowledge consist of unrelated concepts in showing that changes in objects’ motion (i.e. distance travelled, velocity and travelling time) are the results of the fundamental concept of acceleration. The conceptual approach to acceleration as the net force to mass ratio, for gravitational acceleration in particular, serves to clarify the need to simplify real-world situations, emphasizing the relatedness of concepts. In relating motion diagrams and other, different, representations, the coherence of physics concepts and representations is again illustrated. This in turn brings together related mathematics and physics concepts and assists in enhancing the relationship between physics and mathematics.

In addressing the research question: To what extent does the inclusion of motion diagrams in a constellation of multiple representations contribute to student understanding of the conceptual relationships between the physics variables and other representations for free fall motion? we conclude the following: The important factor highlighted by the teaching activity presented here is the necessity to include motion diagrams as fundamental representations. In addition to visualizing the motion of objects motion diagrams also make it much easier to both compare changes in different variables and link the changes to the variables described in physics equations. Therefore, motion diagrams are critical representations in a constellation of representations to enhance student understanding of the conceptual relationships between the physics variables and representations for free fall motion. The fine-grained teaching activity developed for teaching conceptual understanding and the evidence presented in this paper provide the context and justification for our argument for a conceptual qualitative approach towards the design of teaching (and learning) activities for specific introductory mechanics topics.

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