A study of possible causes and remedies of misconceptions in physics from the perspective of information processing

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Abstract
An interesting feature of many of the misconceptions in physics is that they occur worldwide and seem to be independent of culture and learning environment. Moreover, misconceptions are resistant to change and may prevail up to university level. It seems reasonable to deduce from these features that a common underlying mechanism may explain the formation and persistence of misconceptions. The information processing model explains how all knowledge are formed, stored and retrieved in the mind of the learners. One may thus be able to understand and tread learners' misconceptions in terms of how learning takes place. The formation of some misconceptions may even be prevented before they are formed. The study discusses possible causes of misconceptions in the framework of information processing and the constructivist theory of learning as well as possible remedial actions on the basis of conceptual refinement and the variation theory. Examples from mechanics are used to illustrate proposed implementations.
Keywords: information processing model, conceptual refinement, variation theory, misconceptions, Newton's laws of motion

1. INTRODUCTION

Our senses are our only means to gain knowledge. In the physics classroom learners use their senses when solving problems and doing experiments. The information processing model is a simplified model of how we learn and is based on research in the neuro-sciences, psychology and education (Redish, 2004). This model is in accord with the constructivist learning theory that is often applied in the learning of sciences.

The constructivist learning theory emphasises the importance of learners' prior knowledge. According to Ausubel (1968) the most important factor in education is to determine what learners already know and to take it into account when teaching them. Unfortunately, physics education research showed that we cannot simply build onto all existing knowledge that learners posses, because they contain misconceptions that differ from the accepted scientific understanding. Numerous physics education research studies focus on determining and changing misconceptions (e.g. in Duit, 2007). Examples of misconceptions in mechanics are the ideas that a constant force causes an object to move with a constant speed, some force always acts in the direction of motion (so-called force-as-mover misconception) and that a larger mass falls faster towards the earth than a smaller mass (Halloun & Hestenes, 1985). A basic difference between learners' intuitive views about motion and that of physics is that in everyday life situations it is only necessary to distinguish between moving and stationary objects (Redish, 2003), while Newton's laws of motion distinguish between constant velocity motion and accelerated motion.

Some physics education researchers (e.g. Dekkers & Thijs, 1998; Hammer, 2000) argue that productive elements in learners' existing knowledge should be determined and used as resources for building scientific knowledge. On this basis, Lemmer and Lemmer (2010) proposed a conceptual refinement model as didactical model for the learning of physics. According to this model learners' experiential knowledge are refined to conceptual and formal physics knowledge. Lemmer (n.d.) obtained a learning gain of 0.3 in an implementation of this model in a teaching sequence on Newton's second law of motion. This learning gain lies between the averages for traditional teaching and interactive learning (Hake, 1998). This study motivates the addition of aspects of the variation theory (Martin & Pang, 2006) to the conceptual refinement model in order to enhance the learning gain of teaching-learning sequences. While conceptual refinement is a bottom-up approach that starts with learners' prior knowledge, the variation theory can be used as a top-down approach that considers the learning of physics from the perspective of the content that needs to be mastered. Applications of the elaborated conceptual refinement model are discussed.

2. LITERATURE STUDY

2.1 The information processing model, learning impediments and remedial actions

According to the information processing model our minds consist of three components, namely a sensory register, working memory and long-term memory (Figure 1). New information enters the mind through the senses. Only selected stimuli are encoded and transferred to the working memory. The new information cues associated existing knowledge that has been stored in the long-term memory. In the working memory the new and existing knowledge are processed, transformed or combined (Redish, 2004). The result is the storage of knowledge structures in the long-term memory in the form of organized networks of connected knowledge elements.

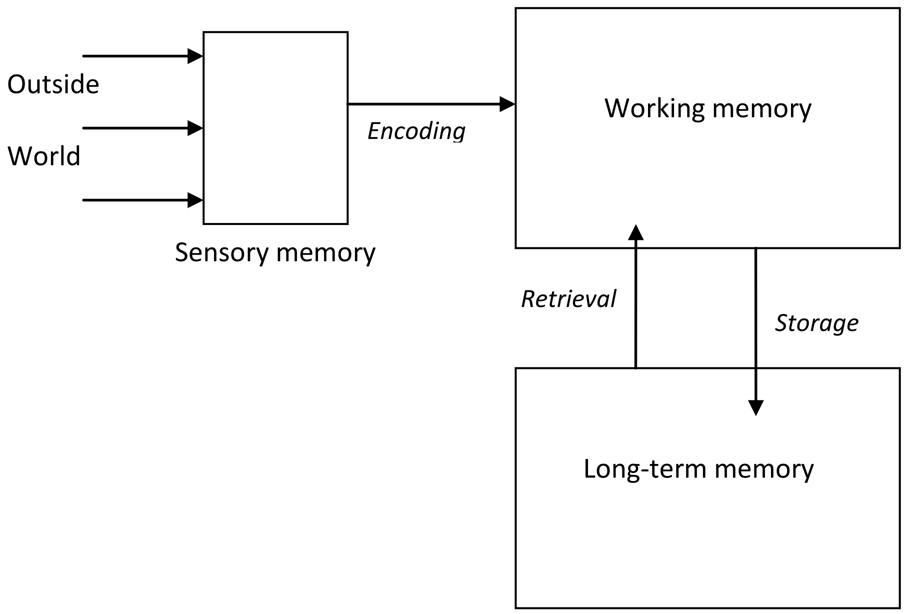

Figure 1: Illustration of the components of memory and the processes between them.

Weiten (2007) distinguished three processes when learning takes place, namely the *encoding* of perceptions of sensual observations, the *retrieval* of existing knowledge from the long-term memory to the working memory and the *storage* of the processed knowledge in the long-term memory (Figure 1). Redish (2004) emphasized the importance of *attention* during the encoding process, *recall* of appropriate information during the retrieval process and *repetition* in order to build strong knowledge structures during the storage process.

The information processing model is in accord to the constructivist ideas of Ausubel (1968) and others. Two key assumptions of the constructivist theory of learning are that meaningful learning necessitates learners' linkage of new material to existing knowledge and that learners' existing cognitive structures determine what will be learned (Taber, 2005). On the basis of these key assumptions, Taber explored possible explanations for students' learning difficulties and compiled a topology of learning impediments (Figure 2).

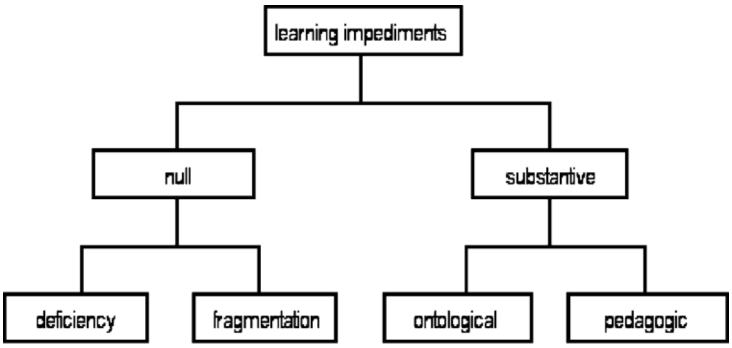

Figure 2. A typology of learning impediments (Taber, 2005).

The first main category (null impediment) in Taber's topology results from a learner's inability to recognize any relevance between the new material and existing material. The nature of this null learning impediment can be due to the non-existence of relevant material in the existing cognitive structure (deficiency impediment) or the non-recognition of such relevance if it exists (fragmentation impediment). Secondly, the substantive category involves ontological impediment when the presented material is inconsistent with the learner's intuitive ideas about the world while pedagogic impediment shows inconsistency between presented material and cognitive structures formed in prior learning. Taber does not consider the classification of ontological and pedagogical impediments as absolute, because alternative conceptions may be derived from interactions between the knowledge learned inside and outside the classroom.

Substantive impediments contain robust knowledge structures that are difficult to cure (Taber, 2005). In the constructivist framework remedial actions of substantive impediments often involve explicating and challenging learners' prior knowledge and misconceptions. Posner, Strike, Hewson and Gertzog (1982) laid down the conditions for effective conceptual change as learners' dissatisfaction with their existing concepts and their acceptance of the scientific concept as intelligible, fruitful and plausible.

According to Taber's topology inconsistency between existing knowledge (retrieved from the long-term memory) and new knowledge (obtained through the sensory register) is a major cause of learning problems. Lemmer (n.d.) showed that deficiencies in application in all of the three processes of information processing (Weiten, 2007) can result in misconceptions. Table 1 summarizes possible learning problems and associative remedial actions for each of these processes.

Table 1: Learning problems and remedial actions associated with the processes in information processing (Lemmer, n.d.)

Process	**Learning problems**	**Remedial action**
Encoding	Emphasis on contextual features Incorrect visual perception	Attention to aspects of importance for learning the concept. Meta-conceptual awareness of limitations in visual perceptions.
Retrieval	Associations to non-related existing knowledge.	Recall of appropriate existing knowledge and known experiences that adhere to the same principle or theory of the overarching framework.
Storage	Knowledge is fragmented. Coherent knowledge structures are not formed.	Appropriate linkage of new knowledge with related existing knowledge. Understanding where the knowledge fits in the science explanatory framework. Repetition to ensure the formation of strong knowledge structures,

With reference to the process of encoding, learners may pay attention to inappropriate contextual features during observations, resulting in perceptions that differ with the intended learning (Lemmer, 2012). Context may distract the learner from the essence of the knowledge that the teacher wants them to learn. Retrieval of irrelevant existing knowledge and conflict between new and existing knowledge may prevent the formation and storage of coherent science knowledge structures (Taber, 2005). Instead of using underlying physics principles or theories to solve problems or explain observations, learners' answers are inconsistent and fragmented (Brown & Hammer, 2008; Lemmer, 2012).

Palmer (1997) found that younger learners are often influenced by their own experience of motion as well as contextual features of the physics problem. When a force is applied to an object, a learner may attend to features of the person exerting the force, while for the scientist the actor is of no importance and the force is only related to the mass and acceleration of the moving object. In a focus group discussion conducted by Lemmer (2012) learners showed contextual reasoning by asserting that a ball rolling on a horizontal ramp moves with a constant velocity due to the short length of the ramp, while it decelerates on a floor where it travels a longer distance. This perception is related to the force-as-mover misconception.

According to Palmer (1997) learners may also reason differently with regard to horizontal and vertical motion. This may be ascribed to differences between the actual velocity of moving objects and the velocity perceived by the learners in everyday life observations (Lemmer, 2012). According to experimental results, people perceive vertical movement to be faster than horizontal movement (Brown, 1931). Another visual limitation that may affect learners' perceptions in kinematics is that we cannot detect changes in speed when the change is small compared to the speed itself (Gottsdanker, 1956). Such limitations may affect the knowledge that is stored in learners' long-term memory and may contradict the physics to be learned, causing substantive impediments.

Remedial actions for learning problems that may occur during information processing are summarized in the last column of Table 1 (Lemmer, n.d.). The terminology of Redish (2004) was used in the formulation of the proposed remedial actions, namely attention, recall and repetition. During classroom observations, discussions and problem solving the teacher should direct the learners' *attention* to the critical aspects of the object of learning. Where appropriate the learners should become aware of limitations in their sensual perceptions. The educator should further ensure (e.g. by asking relevant questions) that learners *recall* appropriate prior knowledge that can be used to understand the intended concept, theory or principle. The process of *repetition* does not imply that the same knowledge element should be repeated over and over again by rote learning. Instead, a variety of situations set in different contexts should be used to allow discernment of critical aspects and to guide learners to generalize the intended knowledge (Lemmer, 2012). Linkages between existing and new knowledge should be emphasized explicitly in order to build and store structures consisting of networks of scientific concepts and relations.

2.2 Conceptual refinement model and variation theory

Lemmer and Lemmer (2010) implemented assumptions of the constructivist learning theory and the information processing model in the conceptual refinement didactical model that can be used to design teaching-learning sequences in physics. According to this didactical model, learners' experiential knowledge is incrementally refined to conceptual scientific knowledge with the aid of a series of carefully selected classroom activities (Figure 3). The conceptual knowledge thus gained is subsequently formalized as a physics law, theory or other physics relations.

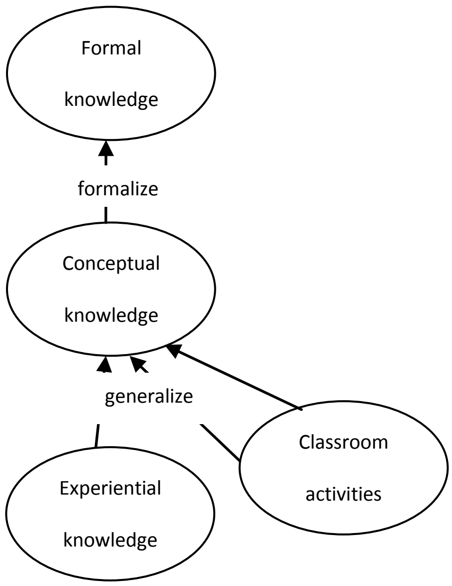

Figure 3: Conceptual refinement model (Lemmer & Lemmer, 2012)

The conceptual refinement model is thus a bottom-up model that develops learners' experiential knowledge to physics knowledge. It is argued that a top-down approach from the perspective of what is to be learned can complement the conceptual refinement model. Such a top-down approach should share the principles of the conceptual refinement model and be relevant in terms of information processing. The variation theory seemed to adhere to these requirements. The variation theory also emphasises learners' experiential knowledge, the direction of their attention (or awareness) to specific features of a concept or phenomenon and the simultaneous discernment of more than one feature to form relationships between critical aspects (Marton & Pang, 2006; Runesson, 2006).

The variation theory is based on phenomenography and asserts that one should experience variability in order to discern a concept or phenomenon (Marton & Pang, 2006). For example, we would not have been able to discern the concept of colour if only one colour existed. Experiencing variation in the critical aspects of a concept or phenomenon, while other aspects remain invariant, is a necessary condition for learning it. According to the variation theory, each concept or topic to be learned has critical aspects that need to be discerned. Hekkenberg, Lemmer and Dekkers (n.d.) compiled a list of critical aspects to discern electric and magnetic fields. Hekkenberg *et al.* showed that learners' misconceptions about electric and magnetic fields can probably be attributed to one or more of the critical aspects that are not discerned.

According to Marton and Pang (2006) the learning that takes place in a sequence of lessons depends on the pattern of variation and invariance in the sequence. The critical aspects and the pattern of variation and invariance differ from topic to topic. Hekkenberg *et al*. discussed how a space of learning was opened in an introductory lesson on magnetic fields by focussing on similarities and differences between electric and magnetic fields. Linder, Fraser and Pang (2006) found that a group of introductory physics students that utilized systematic variation in the learning of Newton's third law outperformed a similar group that was taught in a more conventional way. According to Marton and Pang (2006) teachers who intentionally and systematically make use of patterns of variation and invariance are more likely to succeed.

3. IMPLEMENTATION: TEACHING SEQUENCES ON NEWTON'S SECOND LAW OF MOTION

A possible way to implement both the variation theory and conceptual refinement in a teaching sequence is to first determine the critical aspects to be discerned and then use the conceptual refinement model to compile a series of activities.

(1) Determine the critical aspects to be discerned

A list of critical aspects that needs to be discerned in order to understand Newton's second law is summarized in Table 2. The first critical aspect (1.1) deals with the association between the net force acting on an object and the acceleration caused by it. Learners tend to associate force with the velocity instead of acceleration (Halloun & Hestenes, 1980). In physics acceleration is defined as the rate of change in velocity (aspect 1.2 in Table 2). Both the net force and acceleration can have positive, negative or zero values, but are always directed in the same direction. The relation between the acceleration and the change in velocity is more complex because these two vectors are not always in the same direction as is indicated in Table 2. Newton's second law of motion, as used at school level in South Africa, is a relationship between the quantities of force, mass and acceleration (aspect 2, Table 2). In accordance to the variation theory all three possible variations given under point 2 should be understood for complete discernment of the relationships incorporated in the law.

Table 2: Critical aspects concerning Newton's second law of motion

1.1 Net force is associated with acceleration (NOT velocity)
▪ $a > 0 \Leftrightarrow F_{net} > 0$
▪ $a < 0 \Leftrightarrow F_{net} < 0$
▪ $a = 0 \Leftrightarrow F_{net} = 0$
1.2 Acceleration is defined as the rate of CHANGE in velocity ($a = \frac{\Delta v}{\Delta t}$)
▪ Constant acceleration ➔ constant increase/decrease in velocity

▪	Positive acceleration ➔ increase in velocity in the positive direction or decrease in velocity in the negative direction	
▪	Negative acceleration ➔ decrease in velocity in the positive direction or Increase in velocity in the negative direction	
2.	*Proportional relationships between force, mass and acceleration (F = ma)*	
•	The net force is directly proportional to the acceleration at constant mass.	
•	The net force is directly proportional to mass at constant acceleration.	
•	The acceleration is inversely proportional to mass at constant net force.	

(2) Implement the conceptual refinement model.

After identifying the critical aspects and variation thereof, a series of activities can be selected to generalize and formalize the intended conceptions in accordance to the conceptual refinement model. The model also suggests the order of implementation of the selected learning activities.

Of the three variations under point 1.1 in Table 2, namely $a = 0$, $a < 0$ and $a > 0$, the condition $a > 0$ is probably more in accord with learners' experiences and easier for them to comprehend than the other two. According to Dekkers and Thijs (1998) students often apply this condition correctly in contexts where objects collide, are being pushed, hit, bent or stretched. Although limited, their experiential knowledge can be refined and the contexts of application expanded to aid them in developing the scientific meaning of the concept of force. In this way dissonance may even be resolved before the learners experience it. Since $a = 0$ is least in line with learners' everyday experiences, the proposed order of introduction is the conditions for $a > 0$, $a < 0$ and $a = 0$.

For each one of these conditions, a series of activities set in different contexts can be used to generalize the scientific knowledge. Examples of such series of activities are illustrated in Figure 4. Both series (a) for $a > 0$ and series (b) for $a < 0$ utilize motion on a horizontal plane, a ramp (diagonal motion) and vertical free-fall. This variation in context was chosen to enhance learners' understanding that the same relationship between force and acceleration is always valid, notwithstanding the situation or context. The consistency of application of physics concepts and laws is emphasized to prevent fragmentation and contextualisation of knowledge. Similar contexts are used in the series of (a) and (b) to allow for variation in the condition. In other words, for each condition ($a > 0$ and $a < 0$) the contexts are varied while the condition remained invariant. Then the condition is varied (from (a) to (b)) while keeping the contexts invariant.

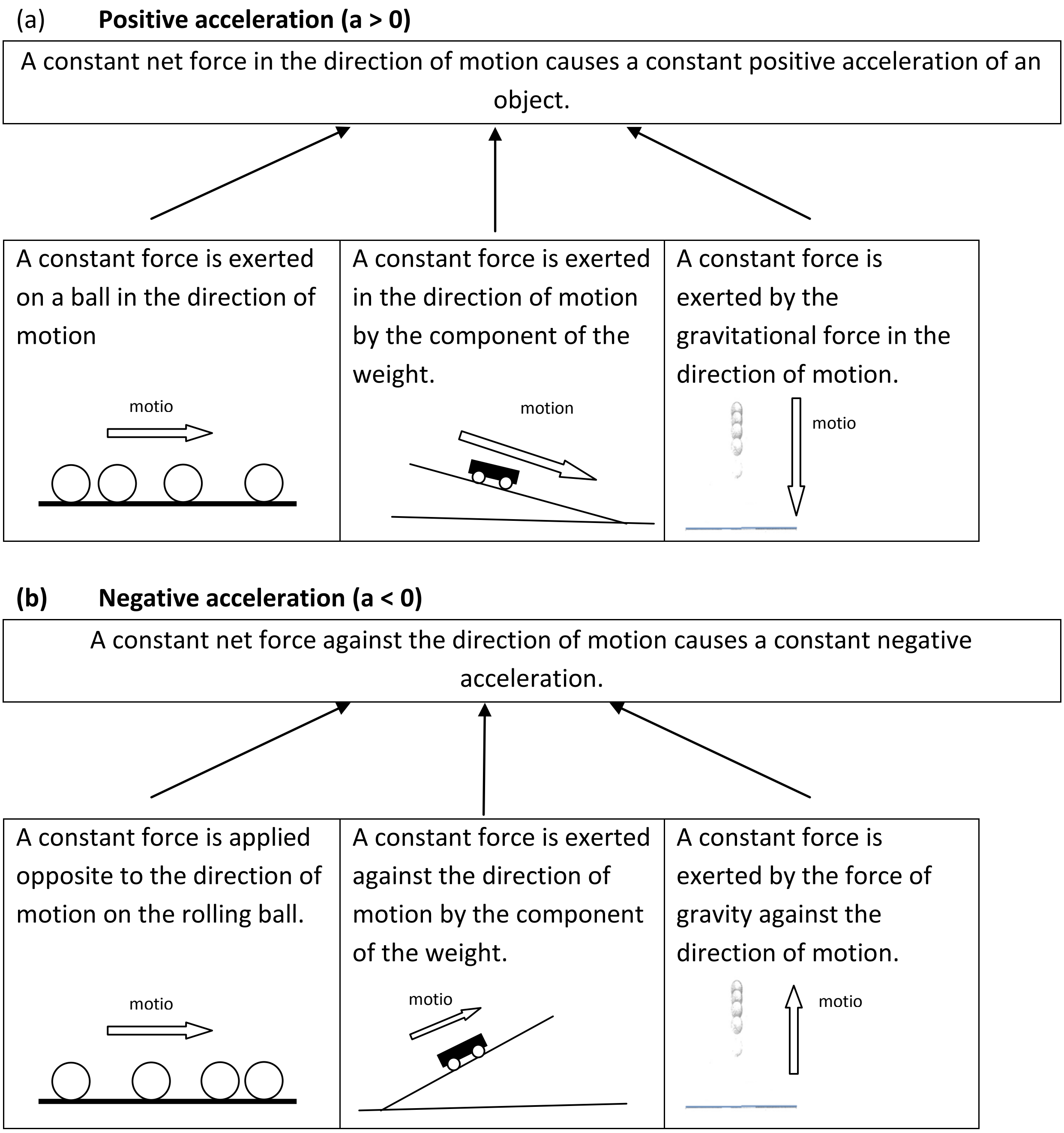

Figure 4. Two sequences of activities in varied contexts to generalize that a constant net force causes a constant acceleration of an object.

Critical aspect 1.2 (Table 2) can be attended to with the aid of a motion detector and real-time kinematics graphs, as was done by Thornton and Sokoloff (1990). It is important to investigate the different variations in a systematic way and in different contexts. Runesson (2006) emphasised the importance of varying one aspect at a time, keeping the others constant. At a later stage more than one variable can be changed simultaneously to investigate more complex situations. Variation in context are needed for building coherent knowledge structures. A meaningful way to evoke learners' awareness of the consistency of physics knowledge is to realise the similarities in the form of the graphs for the motion of trolleys along a ramp with varying incline. Learners can be guided to deduce that horizontal and vertical movements are merely special cases of inclined movements with the angle of incline being 0^0 or 90^0.

Critical aspect 2 regarding Newton's second law of motion (Table 2) includes the addition of mass as a third variable in the law. The first of the proportionalities (namely that the net force is directly proportional to the acceleration at constant mass) followed from previous activities (shown in Figure 4 (a) and (b)). The variation theory proposes that this relationship should be complemented by investigation of the other two proportional relationships, namely the proportionalities between acceleration and mass for constant force and between force and mass for constant acceleration. This should allow for the complete discernment of the proportionalities incorporated in Newton's second law of motion. It is interesting to note that each one of the proportional relationships, if it is not discerned, may cause a misconception that is generally found amongst learners (Halloun & Hestenes, 1980), as given in Table 3.

Table 3. Critical aspects on proportional relationships in Newton's second law of motion and possible misconceptions that may arise if the critical aspects are not discerned.

Critical aspect on proportional relationship	**Possible misconception**
The net force is directly proportional to the acceleration at constant mass	Force is associated with velocity (or motion) instead of acceleration
The net force is directly proportional to mass at constant acceleration	Heavier objects fall faster towards the ground than lighter objects.
The acceleration is inversely proportional to mass at constant net force	During a collision, the larger mass exert the larger force on the smaller mass.

The examples above show different implementations of variation in physics, namely variation in context, in conditions and in relationship between variables. Another way in which variation can be implemented is that of presentation. In most of the sketches given in Figure 4 the motion occurs from left to right and this direction is chosen to be the positive direction. Learners also need to work with situations where motion takes place from right to left, or where the positive direction is not used in the conventional way.

4. SUMMARY AND CONCLUSIONS

Information processing provides a framework for understanding misconceptions and suggests remedial actions in terms of how people learn and new knowledge is formed in the mind. Each one of the three processes of information processing need to be taken into account in order to cure or (where possible) prevent the formation of misconceptions. Learning impediments may be lessened by ensuring that learners pay attention to critical aspects of the intended knowledge, recall appropriate existing knowledge and form science concepts through generalization in a variety of contexts.

The variation theory can be implemented in teaching sequences as a top-down approach that analyses the intended physics knowledge and determines the critical aspects to be discerned. The bottom-up conceptual refinement model can subsequently be used to compile a sequence of activities to incrementally development learners' existing knowledge into scientific knowledge structures. Sequences of activities should implement patterns of variation and invariance in a purposeful, structured, progressive way. Variation in context, conditions, presentation and relationships between variables could be utilized in physics education.

It is recommended that further research is done to evaluate teaching sequences that are compiled in accordance to the proposed didactical model.

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