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Effects of Using Historical Microworlds on Conceptual Change: A P-prim Analysis

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This study examines the effects of using historical microworlds on conceptual change in mechanics. Historical microworlds combine history of science and microworld through a computer based interactive learning environment that respects and represents historic conceptions or theories. Six grade 5 elementary students participated individually to five semi-directed interviews of forty-five minutes each where they interacted with an Aristotelian microworld, a Buridanian microworld and a Newtonian microworld. diSessa's p-prim theory is used to analyze the conceptual dynamics that occurs when students use historical microworlds. Results show positive effects of using historical microworld on conceptual change such as (1) questioning the idea that any object in motion will eventually stop and (2) increasing the importance of contextual elements in the elaboration of explanatory models.

Key Words: historical microworlds, conceptual change, history of science, microworlds, P-prim

Introduction

One of the most spectacular aspects of scientific theories is that, not only can they explain most of the natural phenomena, but they can also make precise and quantitative predictions. In science education, teachers ask their students to predict when solving quantitative problems so that they may acquire an understanding of scientific concepts (Nakhleh, 1993). However, the relation between students' skills in solving numerical or quantitative problems and their real conceptual understanding is not a straightforward one, since students can solve quantitative problems by using mathematical equations and memorized algorithms without really understanding the meaning of the scientific concepts involved in the problem to be solved (Gabel, Sherwood & Enochs 1984; Lin, Hung & Hung, 2002; Nakhleh & Mitchell, 1993). The considerable amount of research studies on students' conceptions showing that students have only a limited qualitative understanding also supports the view that quantitative exercises or problems alone are not sufficient to help students understand scientific concepts (Confrey, 1990; Driver & Easley, 1978; Legendre, 1997; Liu, 2001; Sequeira & Leite, 1991; Viennot, 1979; Wandersee, Mintzes & Novak, 1994). To help promote conceptual change (Posner, Strike, Hewson & Gertzog, 1982), teachers cannot simply ask their students

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to solve quantitative problems; they have to insist on the qualitative understanding of the concepts, because physics' classical instruction does not seems to "affect the fundamental qualitative structures of the students' cognitive systems" (Schecker, 1992).

Before and since Matthews (1994), many researchers have studied the crucial role of the use of the history of science in science education to promote conceptual change and to teach more qualitatively. This is because students' conceptions and past scientists' and philosophers' conceptions are often quite similar (Dedes, 2005; Kousathana, Demerouti & Tsaparlis, 2005; Sequeira & Leite, 1991; Serouglou, Kouramas & Tselfes, 1998; Wandersee, Mintzes & Novak, 1994) – and this is particularly true for the conceptions in the field of mechanics (Matthews, 1990; Sequeira & Leite, 1991). Discussing about historic conceptions might help students to make explicit their own conceptions (Lin et al., 2002; Monk & Osborne, 1997). Moreover, being in contact with historic conceptions can help students realize that their own conceptions have weaknesses (Confrey, 1990; Wandersee et al., 1994). To teach historic conceptions is of special interest to promote conceptual change, since students are often opposed to scientific conceptions for the same reasons as scientists in the past were (Monk & Osborne, 1997). Because there are significant similarities between the development of children's understanding and the evolution of scientific concepts in the history of science (Monk & Osborne, 1997; Nersessian, 1991; Sequeira & Leite, 1991), many researchers think that teaching the historic sequence of a certain field (such as mechanical physics) can help promote conceptual change. Confrey (1990) believes that integrating the history of science in science education has the advantage of demonstrating a sequence of evolution from students' conceptions to actual conceptions. In the same way, Monk and Osborne (1997) think that this integration allows a comparison between both the history of science and students' conceptions and an understanding of their advantages and disadvantages in specific contexts. Moreover, a historic sequence often evolves from simpler to more complex situations and from more intuitive to more abstract conceptions and this might certainly help promote conceptual change. Finally, when the history of science is integrated in a science class, it is possible to focus less on quantitative problem-solving skills and more on meaningful qualitative understanding of scientific concepts.

Another interesting way to teach more qualitatively and to promote conceptual change is to use a microworld. First introduced by Papert (1980), the notion of micro worlds refers to an interactive learning environment (typically computer-based) that allows students to immediately test hypotheses about how this environment works. One of the most interesting aspects about a microworld is that it represents a simplified version of the real world (White, 1992):

> The great advantage of using a microworld is that it can comprise a particular range of phenomena not always possible or convenient to isolate in the "real" world. It is a microworld, much smaller than the real world, with substantial constraints by virtue of its programming and interface on the number of causal factors and on the possible actions students might take (Metz & Hammer, 1993).

With computers, "it is easy to compare through a computer simulation the ideal and the real case" (Bevilacqua et al., 2006). In mechanical physics, microworlds have often been used to promote or study conceptual change (diSessa, 1982, 1986; Legendre, 1995, 1997; Papert, 1980; Potvin, 2002; Potvin, Legendre, & Thouin, 2003; Roth, 1996; White, 1992; White & Horwitz, 1988). Like computer simulations, microworlds provide students with the opportunity "to ask probing 'what if' questions" (Horwitz & Barowy, 1994), and, as Richard, Barowy and Levin (1992) point out, to confront their ideas "with an ensemble of related experiences that [students] themselves come to see as conflicting with their own ideas", a condition deemed necessary for conceptual change. Inspired by Snir, Smith and Grosslight

(1993) and by Richard, Barowy and Levin (1992), Härtel (2000) also believes that computer simulation programs can be "a tool to support the modification of pre-scientific concepts, to acquire and understand new concepts." He also agrees that the use of microworlds encourages a more interactive (or interrogative: McKinney, 1997) and more qualitative approach to science teaching.

Because the evidence from science education research indicates that both the history of science and the use of microworlds might contribute positively to students' conceptual change, we tried to get a synergy of both approaches by developing the concept of "historical microworld" (Masson & Vázquez-Abad, 2006). A historical microworld is a "computer-based interactive learning environment respecting historic conceptions" (Masson & Vázquez-Abad, 2006). The learning computer-based environment is said "interactive" because, like standard microworlds, it allows students to act upon the virtual world by changing some parameters to test hypotheses and see what ensues. A microworld is said "historical" if it respects historic conceptions. By "respecting historical conceptions", we literally mean that the world has been programmed to respect the conceptions of a past philosopher's or scientist's theory. Accordingly, whatever students do, the microworld will show what would happen if the theory of the previous scientist was good.

We developed three historical microworlds, which were extensively described in a previous article published in the Journal of Science Education and Technology (Masson & Vázquez-Abad, 2006). The first, an Aristotelian microworld, respects Aristotle's conceptions of movement (objects in motion naturally slow down and stop; speed is proportional to the force being applied; heavier objects fall faster; etc.) and is subdivided in two situations: (1) a box sliding on the floor (Figure 1a) where students can modify the initial speed, the force that acts upon the box and the mass of the box and (2) two balls falling (Figure 1b) where students can change the mass and, consequently, the volume, because the density of the balls has been programmed to be constant. The second, a Buridanian microworld, respects the theory of impetus (objects propelled in the air fly because we give them an impetus; when all of the impetus is consumed, the objects fall) and is composed of one situation: an arrow propelled in the air (Figure 1c) where the user can change the initial speed of the arrow and its mass. Finally, the third is a Newtonian microworld respecting Galileo's conceptions and Newton's laws of movement (i.e. the principle of inertia; the acceleration is proportional to the force being applied; all falling objects have the same constant acceleration; etc.). It contains two situations: a ball rolling on three different inclined u-shaped planes (Figure 1d shows one of the three inclined planes) where students can change the initial position of the ball, and a ball released from the top of a navigating ship (Figure 1e) where students can modify the ship's speed and the power of the kick of the ball toward the right to obtain different initial velocities.

This paper analyzes the effects of the use of these three historical microworlds on conceptual change in mechanics. Further to the presentation of the theoretical framework based on diSessa's p-prim model of conceptual change (diSessa, 1993), more precise and operational research questions will be presented. Finally, results will be discussed after having described the methodology of the research.

P-Prim model of conceptual change

To know the effects of using historical microworlds on conceptual change, a definition of the latter is needed to analyze the data. Among all the models of conceptual change (for example Chi, 1992; Posner et al., 1982; Vosniadou, 1994), we choose diSessa's p-prim one (diSessa, 1993), because it is a well-articulated model and appropriate to describe the dynamics of conceptual change (Potvin, 2002; Southerland, Abrams, Cummins, & Anzelmo, 2001) and, therefore, to describe what is happening during the use of historical microworlds.

Thus, in this research, we are not only interested in the difference between conceptual comprehension of the students before and after having used the historical microworlds. We are, in fact, more interested to see what happens during the exploration of the microworlds.

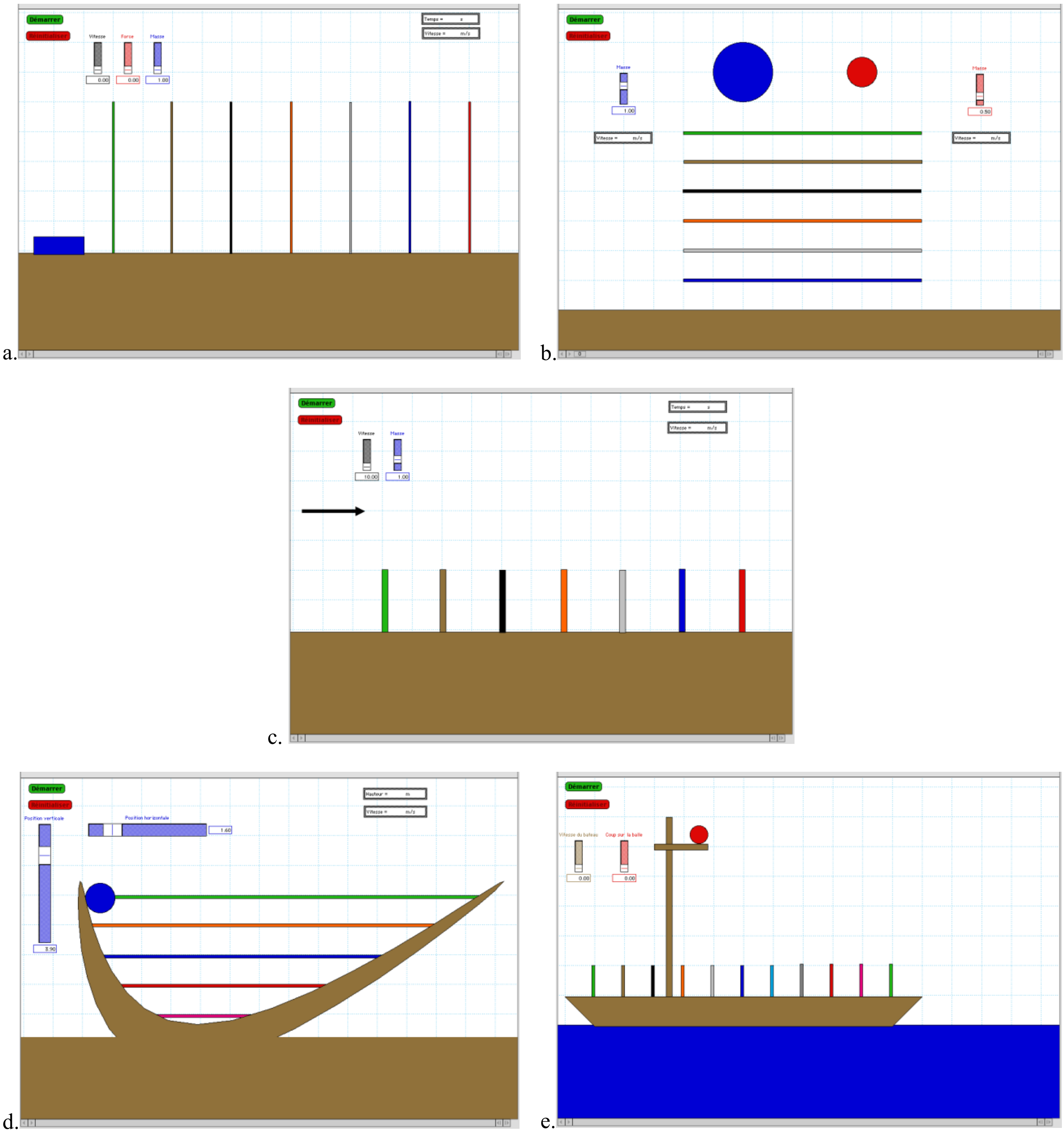

Figure 1. Aristotelian (a and b), Buridanian (c) and Newtonian (d and e) microworlds used in this study.

We want to know when and how do the students' conceptions change. We are interested in the dynamics involved during the conceptual change process. In this section, the central concept of diSessa's model of conceptual change, the concept of phenomenological primitive (p-prim), is defined, the cognitive mechanism by which the p-prims are activated is explained and the nature of conceptual change from diSessa's point of view is discussed.

The concept of p-prim

To explain by which mechanism the students formulate their conceptions, diSessa (1993) introduces the notion of phenomenological primitive (p-prim). A p-prim is a primitive cognitive tool or a general structure of qualitative reasoning that helps the student formulate intuitive, spontaneous conceptions about many natural phenomena. When a student is placed in an environment involving some scientific concepts like force, mass, movement and others, he tries to establish relations between those concepts and the data he receives from the environment. P-prims help to link scientific concepts with each other, because they are like small pieces or structures of qualitative reasoning that help students relate primary sensory data with relatively conscious ideas and concepts. Some of them, such as the one used in this study, are like empty, qualitatively related boxes in which students place physical parameters to try to explain natural phenomena. Among the many p-prims described by diSessa (1993), we discuss here only those relevant to this research: Ohm's p-prim, dying away, canceling and overcoming.

The Ohm's p-prim has the same knowledge structure of Ohm's. This p-prim comprises three sub-entities: "an agent that is the locus impetus that acts against a resistance to produce some sort of result" (diSessa, 1993). In Ohm's law, the electric potential (U) is the agent that creates an electric current (I) against a resistance (R). The higher the agent (U) is, the higher the result (I) will be. This is the first part of Ohm's p-prim: the proportional relation between the agent and the result. The second part of the p-prim is an inversely proportional relation between the resistance and the result: for a particular agent's intensity (U=constant), the higher the resistance (R) is, the lower the result (I) will be.

The p-prim dying away is used when someone wants to explain why something is fading until it dies. For example, the amplitude of a pendulum is going lower and lower until it stops. A hot soup is going colder and colder until its temperature becomes the same as the environment. Another p-prim, canceling, can be activated when we can see no result in a situation involving two equal and opposite agents. A classical example is when two persons are pushing each other with the same intensity and do not move. Finally, the p-prim overcoming is involved when the canceling described previously is broken because one of the opposite agents acts harder than the other. Then, if a person pushes harder than the other, it seems for a third person that one person pushes toward the other because the second person walks back.

Cognitive mechanism of p-prims

The central concept to explain the cognitive mechanism of p-prims is recognition. According to diSessa (1993), p-prims are activated when students recognize that sensory data might be interpreted or assimilated with a particular p-prim. More precisely, recognition "means being cued to an active state on the basis of perceived configurations, which are themselves previously activated knowledge structures" (diSessa, 1993). To explain the dynamics of conceptual change, the concept of recognition is not sufficient.

Table 1. Symbolic representations of some p-prims.

Symbolic representations
$\text{Result} \propto \dfrac{\text{Agent}}{\text{Resistance}}$
$\text{Result} \rightarrow 0$
$\text{Agent}_1 = \text{Agent}_2 \Rightarrow \text{Result} = 0$
$\text{Agent}_1 > \text{Agent}_2 \Rightarrow \text{Result} \neq 0$

Other concepts are needed to describe the sequence of activation and how an activation state can be related to another. For that, diSessa (1993) introduces the concept of "cuing priority".

"Cuing priority" is the "way a particular p-prim's transition to an active state is affected by other previously activated elements" (diSessa, 1993). We say that there is a high cuing priority when a p-prim is easily activated by the antecedent cognitive context and that there is a low cuing priority when a p-prim is not easily activated by the previous context. An analogy given by diSessa (1993) helps to understand the concept. If there is a flock of individuals near you, you will most probably become tense and nervous and may panic and flee. One element comes after the other and they are highly related. Thus, there is a high cuing priority between flock-of-individuals-in-proximity and tense-and-nervous, and between tense-and-nervous and panic-and-flee.

Definition of conceptual change

For diSessa (1993), learning occurs whenever a person changes the way he or she uses p-prims. The aim is to make a good use of the good p-prim in the good context. Often, student does not use the good p-prim or does not use it correctly. So, this student has to change the way he or she uses p-prims to learn. In this theoretical framework, conceptual change is viewed as a process where the learner works to organize and structure his or her knowledge with the aim to systematically use correctly the good p-prims in the good contexts.

Then, if we want to describe the effects of using historical microworlds on conceptual change from a diSessa's point of view, the research questions become:

- Does the use of historical microworlds activate students' p-prims? If yes, which ones and how do they use them?
- What are the cuing priorities involved while using the historical microworlds?
- How does the use of p-prims change during the use of the historical microworlds? Does the use of historical microworlds push the student to abandon p-prims initial use?
- Does the use of historical microworlds help students to organize and systematize their use of p-prims?

Methodology

To answer these questions, a multicase study based on almost thirty hours of semi-directed interviews was conducted with six elementary grade-5 students from a scientific school in Montreal, Canada. The students had not already received a formal introduction in mechanical physics at their school, but they may have heard about gravity and force in an informal way at extra-academic or family activities. The students were volunteers and participated in this study after classes. They were not chosen for their academic results, but based on their availability. Students knew that the aim of the study was not to evaluate their performance, but to learn about how they use the microworlds. The consents of the school, the teachers, the students and their parents were obtained and all ethical considerations were respected.

Interviews were conducted in an office at the students' school where the computer and the recording material had been installed. We recorded what we saw on the computer's screen and what the student said. On the recordings, we cannot see the child, but only hear his or her voice and see what he does with the microworlds. Once a week during five consecutive weeks, each subject was interviewed during forty-five minutes, for a total of approximately four hours and a half. If we combine the interviews of all the six participants, we obtain twenty-seven hours of research material to analyze. The interviewer took notes about the key events of the interview only after the student left the office.

The role of the interviewer was not to ask why the student made a particular choice and not another, but to propose goals to reach and to encourage the student to talk about what he or she was doing. As already mentioned, the interviews were semi-directed, meaning that the interviewer had general interview protocol lines in mind, but his questions depended on what the student talked about. Generally, an interview followed these steps: (1) interviewer lets the student explore the situation by himself or herself, (2) interviewer proposes goals to reach - while the student tries to reach these goals, the interviewer encourages him or her to speak and, if necessary, asks him or her to explain in a more detailed way or reformulate his or her explanations in order to have a real understanding of what the student is talking about - (3) the interviewer asks the student to resume what was significant for him or her in the situation explored.

To help the reader have a better view of how the interviews were conducted and what questions were asked to children, consider an example from the first situation. Situation 1 of the Aristotelian microworld presents a box sliding on the floor where students can choose the initial velocity or modify the mass of the box. Because it is an Aristotelian world, the things that move always slow down and eventually stop. This is what happened with the box, whatever the initial velocity or mass the student selects. The interview begins with a free exploration to see if the student is surprised by the fact that the box slows down and stops. After that, the interviewer proposes goals to reach. Colored lines are painted on the back wall of the situation and the interviewer uses them to set the goals in order to explore the effects of the initial velocity and the mass of the box: "Could you make the box stop at the yellow line?" "Just by changing the mass, could you make the box stop at the red line?" "If you can change the mass and speed of the box, what will you do to make the box slid the fastest?" After having explored all three historical microworlds, the interviewer proposes to review rapidly the five situations, but this time, the student can change other parameters such as air resistance, friction or gravity.

When the interviews were finished with our six students, we listened and watched the recordings and we resumed on paper each interview. Typically, these summaries contain the highlights of the interview and the choices students made for parameters values. Summaries and notes taken by the interviewer were reviewed. Then, based on the richness of their dialogues, interviews of two students were transcribed (Vincent and Camille). This represents almost eighty pages of verbatim for each subject. All parts of the texts where students expressed conceptions, had doubt about their conceptions or changed their conceptions were highlighted. In order to be reported in this paper as an effect of the use of historical microworlds on conceptual change, it must be present not only in the interviews transcribed, but also in the interviews of each of the four other students (Clara, Simon, Cassandra and Hadrien) for whom we have only made summaries. This is a way to triangulate the data. If the summary was not sufficiently detailed, we returned to the recordings in order to be sure to interpret correctly the student's dialogue.

Results

In this section, we present the observed effects of using historical microworld and we answer to the research questions mentioned at the end of the section "P-prim Model of Conceptual change".

What are the effects of using historical microworld?

Table 2 shows the observed effects when students interact with each of the three historical microworlds and when they reuse them. As previously stated, to appear in the list, an effect must have been observed in each of the six interviewed students.

Table 2. Effects observed during the use of the three historical microworlds.

Microworlds	Observed effects
Aristotelian microworld	Activation of the p-prim *dying away* Activation of *Ohm's p-prim* Activation of the p-prims *canceling* or *overcoming*, but only when *Ohm's p-prim* cannot explain the observed phenomenon
Buridanian microworld	Questioning with hesitation the use of the p-prim *dying away* and beginning to consider the principle of inertia as an alternative Questioning the idea that mass always causes a resistance to movement, but not understanding why the mass of an object can sometimes help this object to continue its linear movement at the same speed
Newtonian microworld	Use of both the p-prim *dying away* and the principle of inertia without being able to explain why using one or another Contextualization and complexification of the criteria that determine what are the good uses of the p-prim *dying away*
Reusing the three historical microworlds	Progressive stabilization of the use of the principle of inertia *Cuing priority* of the notion of friction is progressively getting higher during the use of the microworlds

The Aristotelian microworld permits to activate some p-prims like the p-prim *dying away*. For example, at the end of situation 1, Camille says: "The speed slows down after a certain time, because the speed will decrease." For her and the others, it is simply normal that objects slow down and stop. Students do not seem to need to justify their claims: it is just the way it is.

The *Ohm's p-prim* is also activated during the use of the Aristotelian microworld. In situation 1, all students say that the speed is proportional to the applied force and inversely proportional to the mass:

> Interviewer: If you push on the box and walk at the same time toward the box, what happens?
>
> Vincent: Well, it will be a continuous force, and then the box will always move forward.

Interviewer: How will it move forward? Can you describe its movement?
Vincent: It will slide.
Interviewer: What will happen at the speed of the box?
Vincent: The speed will stay stable; it will depend just on our [walking] speed.

And few minutes after that, when Vincent explores the effect of the mass on the movement, he says: "Heavier is the mass, slower the box will move. Then, when the box is heavier, then it is harder to make it moves".

In situation 2, the *Ohm's p-prim* is also activated to describe the fall of the balls. For example, Camille thinks that "[i]f the mass is bigger, if for example the blue ball is bigger than the red ball, it will fall faster than the red." This use of the *Ohm's p-prim* (more mass causes more speed) is shared among all six interviewed students.

The p-prims *canceling* and *overcoming* are activated, but only when the *Ohm's p-prim* cannot explain the phenomenon. When, in situation 1, Camille realizes that the box has not move, she tries to explain what happened in terms of *canceling* and *overcoming*: "The box has not move because the mass is higher than the speed". And when the interviewer asks her what to do to make the box goes at a constant speed, she said: "I will equalize the speed and the mass".

If students use intensely and unconditionally the p-prim *dying away* in the microworld respecting Aristotle's principles of movement, when using the Buridanian microworld they sometimes begin to have doubts about the validity of using this p-prim in all contexts, especially when students imagine a world without gravity. Camille (situation 3) sometimes thinks that the arrow without gravity will stop, but sometimes not:

Interviewer: If there was no gravity, if we were not on Earth, what would happen with the arrow?
Camille: It would continue.
Interviewer: It would continue, how?
Camille: It would continue all the time.

But only few moments after that, she changes her mind without even really realizing it:

Interviewer: What will be the movement of the arrow from the moment that it is propelled with a speed of 50 until it reaches the ground? […]
Camille: It would go less and less fast, because, although there is no gravity, the speed will decrease. The arrow will move less and less fast.

The same thing happens with all the six students: they hesitate between the p-prim *dying away* and the use of the principle of inertia. During students' exploration of situation 3, when they see the propelled arrow going further when its mass is bigger, students do not understand because they think the mass is a resistance to movement, and they get confused:

Interviewer: Before we begin the situation 4, could you tell me what you remember from the situation 3?
Vincent: I remember it was strange, because, when the mass was lower, the arrow goes less farther.
Interviewer: You say that it was strange?
Vincent: Yes, because when we make planes, we try to use lightweight materials to make it fly better. Usually, when it is heavy, it falls more. Then, I found it strange.

When using the Newtonian microworld, the students use both the p-prim *dying away* and the principle of inertia to explain what they are seeing without knowing why they use one or the other. In situation 4, Camille is not sure: "The ball will always oscillate or it will slow down [...] It will certainly stop, except if it does not stop."

After that episode of confusion, students try to contextualize when the p-prim *dying away* is appropriate and when it is not. Vincent distinguishes when there are gravity, friction and air resistance from the contexts where there are none. Camille does not systematically use gravity, friction or air resistance as important contextual elements, but she uses less abstract elements such as the shape of the inclined planes or the mass of the ball.

Finally, when students reuse the three historical microworlds with the opportunity to modify more parameters such as gravity, air resistance and friction, they use more systematically the principle of inertia and this seems highly related to the increase of the cuing priorities of the notion of friction and air resistance. Indeed, many explanations given by the students link the fact that the object will continue to move with the presence or absence of air resistance or friction: "if there is no air resistance, maybe the box will continue to move", "it will always slide, because there is no friction" (Camille, when she reuses situation1). Same thing for Vincent (when he reuses situation 4): "without air resistance, without friction and with gravity - we'll begin with that - [...] the ball will go down and never stop".

Does the use of historical microworlds activate students' p-prims? If so, which one and how do they use it?

The first step to make students change their conceptions and to promote conceptual change is to encourage them to make explicit their own conceptions and the p-prims underlying them. Interacting with the historical microworlds involves using some p-prims. Table 3 shows the p-prims used by students to interact with the historical microworlds and how they used them. *Dying away* is constantly solicited. For all subjects, it is normal that moving objects slow down until they stop, since constant movement is not a normal state, this one being rest. *Ohm's p-prim* is activated in two different ways. In one, the force (agent) induces constant velocity (result) against the mass of the moving object (resistance). In the second, the mass (agent) influences the falling speed (result).

Table 3. P-prims used by students during the exploration of the historical microworlds.

Activated p-prims	How students use them
Dying away	Velocity $\rightarrow 0$
Ohm's p-prim	Use #1: $\text{Velocity} \propto \frac{\text{Force}}{\text{Mass}}$ Use #2: $\text{Falling Speed} \propto \frac{\text{Mass}}{\text{Not mentionned}}$
Canceling	Use #1: Mass = Velocity $\Rightarrow$ Acceleration = 0 Use #2: Mass = Force $\Rightarrow$ Velocity = 0
Overcoming	Use #1: Mass > Velocity $\Rightarrow$ Velocity $\rightarrow 0$ Use #2: Mass > Force $\Rightarrow$ Velocity $\neq 0$ Use #3: Gravity > Force $\Rightarrow$ Velocity $\rightarrow 0$

The greater mass is, the higher the falling speed will be. In contexts where students cannot explain what is happening based on *Ohm's p-prim*, they use the p-prims *canceling* and *overcoming*. For example, students said that an object does not accelerate because the "mass factor" equals the object's "velocity" or that an object does not move because the mass is as big as the force produced upon the object.

What are the cuing priorities involved while using the historical microworlds?

We are not only interested in how students improved their conceptual understanding after using historical microworlds, but we are also, and especially, interested by the conceptual dynamics that occurs while students are using historical microworlds. For this reason, we analyze here the cuing priorities involved when a student interacts with historical microworlds to see if that dynamics contributes to promote conceptual change.

In Figure 2, the low or high cuing priorities refer to how much the historical microworlds cued a p-prim or another cognitive element such as the principle of inertia, friction or air resistance in the student's mind. Results show that there is a strong cuing priority related to Ohm's p-prim, since students use it often, spontaneously, and without hesitation or thinking. The p-prims *canceling* and *overcoming* are used only when *Ohm's p-prim* cannot explain the phenomenon, so they have a low cuing priority. These p-prims do not come to mind easily. They need a particular context (impossibility to explain a phenomenon with *Ohm's p-prim*) to be activated.

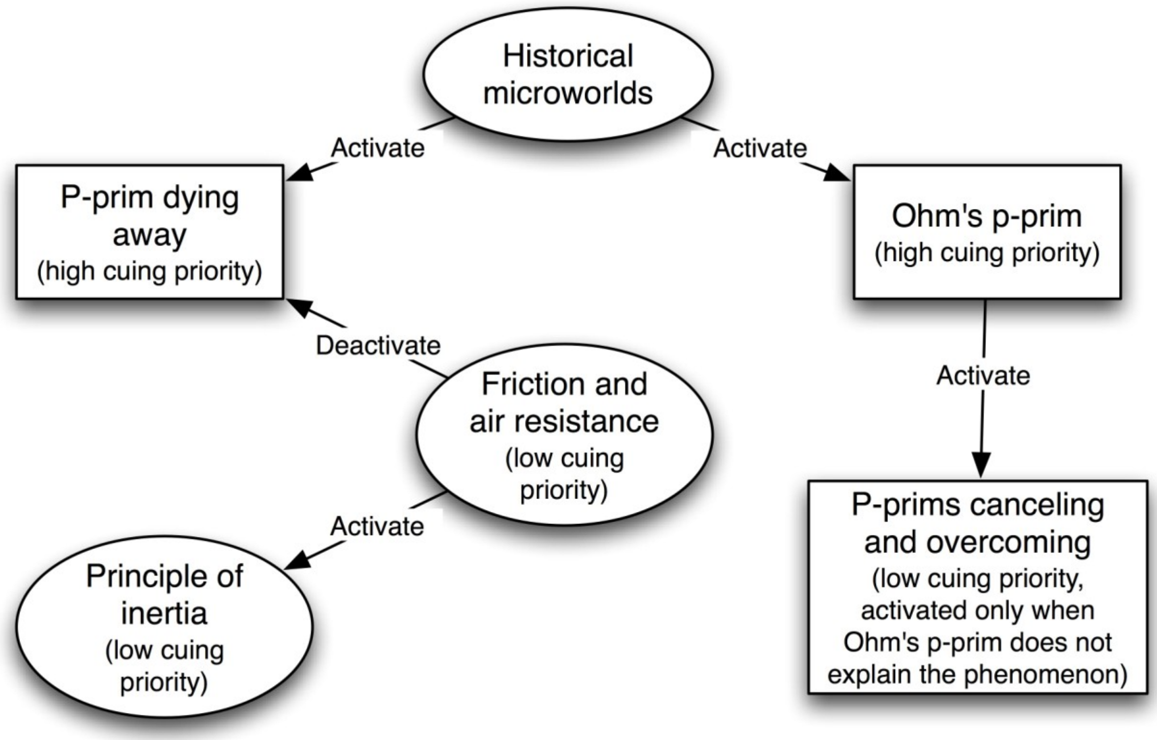

Figure 2. Cuing priorities involved during the use of historical microworlds.

A more interesting structured priorities network for conceptual change is described in the left part of figure 2. It relates the *dying away* p-prim with the principle of inertia through the use of the notions of friction and air resistance. *Dying away* has a really high cuing priority. Students use it constantly in the historical microworlds without considering the role of friction and air resistance. Results show that it is normal for students to see things slow down and stop. When they use the Aristotelian microworld, they never say that objects can move constantly without pushing them (principle of inertia). Moreover, they do not say that objects are slowing down because of the friction or air resistance. In fact, and this is very important for the conceptual dynamics to promote conceptual change through historical microworlds, the principle of inertia and the notions of friction and air resistance have a very low cuing priority: students do not use or mention them.

Friction and air resistance have a low cuing priority. It is a very important result because the notions of air resistance and friction seem to have a central role in the change between the use of the p-prim *dying away* and the use of the principle of inertia. This principle has a low cuing priority, because students do not use it spontaneously; they use preferentially the p-prim *dying away*. In the Buridanian microworld where an arrow is propelled in the air, the friction is lower. So, to explain why the arrow does not slow down and simply stop, they have to think about friction or air resistance. When it happens – because the student begins to use it or because the interviewer uses for the first time the words friction or resistance - it marks the end of the unconditional use of the p-prim *dying away*:

> Interviewer: You said to me many times…
> Student: [It will slow down and stop] like everything! [Laughs]
> Interviewer: Exactly. When we propelled an arrow, you said that it is like everything else: in time the moving object will stop. […]
> Student: Well, if there is no friction [this is the first time that the student uses this word], yes, it will stop at one moment or another … Oh, but no! Not even that, no!

After that sudden revelation that friction exists, this student is able to use the principle of inertia. Also, the context in which objects stop is clearer: "[T]he speed slows down because there is air resistance. But, when we remove air resistance, the speed is stable." This example, like the verbatim of other interviewed students, shows that the notions of friction and air resistance decrease considerably the level of cuing priority of the p-prim *dying away* that passes from a higher to a lower one. At the opposite, the notions of friction and air resistance also increase the cuing priority of the principle of inertia: it changes from low to high cuing priorities.

How does the use of p-prims change during the use of the historical microworlds? Does the use of historical microworlds push the students to abandon their initial use?

We present in this section the steps of the conceptual evolution of the students who used historical microworlds:

- In the beginning, students use trustingly, spontaneously and unconditionally the p-prim *dying away* to explain or predict the movement of an object.
- Placed in the Buridanian microworld where the p-prim *dying away* is not unconditionally true, students question with hesitation the pertinence of the use of that p-prim.

- After that, students use inconstantly the p-prim *dying away* or the principle of inertia. They do not know when they use one or the other. It is more a guess than a certainty.
- Then happens one of the most fruitful events for conceptual change: students interact with the microworld to limit the context of validity of the p-prim *dying away*. They ask themselves: “In which context the moving object will or will not stop?” It is at this point that friction and air resistance begin to have a higher cuing priority.
- Finally, when criteria are found to determine whether the moving objects will stop or not, students stabilize their use of the principle of inertia. But, at the end of the interviews, this stabilization is still fragile and was made by all students but not with the same degree.

Does the use of historical microworlds help students to organize and systematize their use of p-prims?

As we discussed previously, diSessa defines conceptual change as a process where the learner works to organize and structure his or her knowledge with the aim to systematically use correctly the right p-prims in the right contexts. Did it happen? Did the students organize and structure their knowledge during the use of the historical microworlds?

At the beginning of the interviews, when students used the Aristotelian microworld, it is hard to say if students’ knowledge about force and movement is well organized and structured (this question is still in debate: Clark, 2003; diSessa, Gillespis, & Esterly, 2004; Kaufman, Vosniadou, diSessa, & Thagard, 2000; Southerland, Abrams, Cummins, & Anzelmo, 2001). They use systematically the p-prim *dying away* but the reason is not systematically explained.

At the middle of the interviews, when they interacted with situations where objects do not rapidly or clearly stop, students’ use of the p-prims is not systematic. They hesitate. They are surprised of what is happening in the microworld. They are confused. In the last interviews, after this period of confusion, it is clear that students work on the organization of their knowledge. They interact with the microworld in order to find when and why a moving object stops or not. They elaborate progressively a list of criteria including words such as friction and air resistance. Therefore, we can say that historical microworlds helped students organize their knowledge and, in that sense, they help to promote conceptual change. At the end of the interviews, this organization is not perfectly stabilized but is in progression for all students.

Conclusion

Conceptual change is a complex, hard-to-achieve process and this is why we tried to develop a new tool to help promote it, namely the historical microworld. In combining the advantages of both history of science in science teaching and the use of computer microworlds, we programmed three historical microworlds in mechanics based on Aristotle’s principle of movement, Buridan’s theory of impetus and Newton’s laws of movement.

Semi-directed interviews with six elementary grade-5 students show encouraging results: microworlds helped promote students conceptual change by pushing them to organize their knowledge by structuring and contextualizing the domain of validity of their intuitive conceptions. Another key result is that the notions of friction and air resistance seemed to play a central role in inhibiting students’ spontaneous use of the p-prim *dying away* and encouraging them to use the principle of inertia to explain phenomena related to movement. But these notions do not come to students' mind easily; they have a really low cuing priority. Hopefully, because they are simplified interactive worlds that follow an historic sequence from the more intuitive and grounded to a more idealized and frictionless world, historical microworlds seemed to help students integrate air resistance and friction in their discourse more spontaneously.

However, the results presented here have limits. Because we wanted to analyze the effects of using historical microworlds that occurred during the conceptual change process and not only after the use of the microworlds, we had to make some methodological choices, especially concerning the number of subjects. Indeed, only six students were involved in this study resulting in almost thirty hours of interviews to analyze. Although we reported in this paper only the unanimous effects that were observed in the interviews of each case study, it is preferable to see the effects reported in this study not as generalized effects, but as examples of the possible effects of using historical microworlds.

The concept of historical microworld seems to us a promising research avenue for the study of conceptual change. Among possible future developments in that scope, we propose to study the possibility to export the notion of historical microworld in other fields than mechanical physics such as electricity and chemical reactions.

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