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Problem-centered learning vs. teaching-centered learning in science at the secondary level: an analysis of the dynamics of doubt

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ABSTRACT

This exploratory research describes and compares how doubt evolves while learning about electricity in two different learning contexts: problem-centered and teaching-centered. It provides descriptions of performance variations when Secondary 2 to Secondary 4 students begin appropriating basic electricity knowledge with attitudes of either certainty or uncertainty in the two aforementioned contexts. A simple classification of every test answer under five categories ("legitimate certainty", "legitimate doubt", "under-estimation", "over-estimation" and "do not know") was used to track how students' answers migrated from one category to another, and allowed researchers to monitor how students' "certainty vs. doubt" profile evolved in conjunction with variations in their performance. Results indicate, among other things, that problem-centered learning approaches seem to be more profitable for students who express at least a little certainty about their answers, and that teacher-centered approaches seem to be more appropriate for students who express doubts. Results also suggest that problem-centered approaches better prevents the development of unexpected conceptions.

INTRODUCTION

This research explores how initial certainty and doubt influence knowledge acquisition. This exploration was made in two different contexts: a problem-centered learning content and teaching-centered learning context, enabling descriptions and comparisons. The article first describes the general role of doubt in the process of knowledge acquisition, and more specifically scientific knowledge acquisition, and then concentrates on the differences between two fundamentally different ways to learn in school.

Problem-centered approaches for K-12 science classes

Meta-analyses of the effects of problem-centered approaches to student learning usually report that such pedagogical approaches are generally beneficial for students (Hmelo-Silver, 2004; Levy, Minner, & Jablonski, 2007; Vernon & Blake, 1993). While this type of research does not always clarify what qualifies as "problem-centered", it seems to have has a positive effect on explanation construction skills (Wu & Hsieh, 2006), knowledge about the nature of science (NOS) (Akerson & Hanuscin, 2007), motivation and responsibility (Galand & Frenay, 2005; Wu & Hsieh, 2006), and metacognitive and reflective skills (Hmelo-Silver, 2004). The research also suggests that problem-centred approaches prevent the development of misconceptions (Akinoglu & Tandogan, 2007).

Although much enthusiasm about problem-centered approaches can be noted, scant research exists that can be used to elucidate the implementation of this type of pedagogy in the context of K-12 science classes (Hmelo-Silver, 2004). Two reasons stand out to explain this state of affairs. First, comparing the effects of problem-centered learning to other pedagogical approaches is a very difficult task because it often doesn't aim to develop the same competencies in learners. Where more traditional approaches to teaching (such as *direct teaching*) are not as suitable for the development of high level skills (such as open *problem solving*), problem-centered approaches appear to provide a fertile terrain. If the targeted performances are different in nature, comparison between the two treatments might appear akin to comparing apples with oranges, or will often lead to a debate about the purpose of education rather than its effectiveness. Moreover, and quite understandably, K-12 teachers—many of whom work every day with overcrowded classes and are constantly managing demanding situations (Perrenoud, 1996)—might be very reticent to adhere to research results that cannot clearly demonstrate the superiority of methods that can be more time consuming, over those they deem to have yielded "proven" results. Secondly, research on problem-centered approaches to teaching has not focused primarily on K-12 science education, but more on post-secondary education. Hmelo-Silver (2004) suggests that constraints and difficulties typical of K-12 science education (and common across classrooms at this level) such as classroom organization, subject-domain centered curricula, and instructional periods of 50 to 75 minutes in duration, are likely to be factors explaining the lack of research in this area. Therefore, more research is needed to enlighten the effects of pedagogy at these levels.

Science and doubt

The present study is based on two fundamental assumptions. The first was well articulated by Vygotsky almost a century ago.

> "The state of development is never defined alone by what has matured. If the gardener decides only to evaluate the matured or harvested fruits of the apple tree, he cannot determine the state of his orchard. The maturing trees must also be taken into consideration. Correspondingly, the psychologist must not limit his analysis to functions that have matured; he must consider those that are in the process of maturation" (Vygotski, 1997, p. 203).

This suggestion has not, in our opinion, been given enough consideration by the research community, likely because the claim contains a subtle problem: What might constitute reliable clues for identifying less-than-fully matured functions? Simple performance evaluations, such as content questions, are not necessarily well suited to the task. At best, they can attribute partial scores for partially good answers, but it could be argued that these merely reflect the existence of fully-developed sub-functions. This leads into the second fundamental assumption of this research: in science, the idea of doubt (or skepticism) has long been—and still is—often acknowledged as an intermediate and rather rarely assessed state of understanding, a prerequisite for the development of scientific knowledge. Many classical scientists, philosophers, and even poets (Aristotle, Bacon, Galileo, Descartes, Alain, Voltaire, Kant, and Feynman, to name a few) have recognized (in famous and often well-known quotations) the role of doubt as being at the source of scientific progress. Other epistemological arguments have carried on the idea that science is all about doubt and uncertainty (Barrette, 2005; Morin, 1977). Science is therefore often depicted not as an activity that aims to discover truth, an endeavour which is often philosophically presented as impossible, but rather as a process that essentially aims to discard inappropriate models and hypotheses, leaving the most resistant ones standing (Popper, 1995). In this refutational perspective, doubt and dissatisfaction (Strike, Posner, Hewson, & Gertzog, 1982) are perceived as active agents of scientific progress, whereas certainty becomes an impediment to such progress.

Doubt and learning

Doubt is not only a condition for scientific progress and learning at the level of scientific communities. It is also considered important for individuals. Our review of the literature suggests these conclusions:

1. Doubt is an important part of cognition in humans (Brown, Bransford, Ferrara, & Campione, 1983; Dunlosky & Nelson, 1992; Flavel, 1979; Koriat, 1993; Metcalfe, 1994; Nelson, 1992; Nelson & Dunlosky, 1991; Reder & Shunn, 1996), and even in animals (Smith, Shield, & Washburn, 2003), and is therefore an important part of learning.
2. Doubt and uncertainty (Gigerenzer & Todd, 1999) influence learning performance. Some research suggests that since it is linked to self-worth, doubt can have dramatic negative effects on performance (Thompson & Dinnel, 2007). But doubt is also related to self-efficacy (the belief that one is capable of performing in a certain manner to attain certain goals), which has been shown to have positive effect on performance (Pajares, 1997; Schunk, 1989). There is, in short, no established consensus at the moment about the contributions of doubt and uncertainty.
3. Doubt can influence learning performance positively or negatively other intervening factors. Among these are the level of previous knowledge, the type of pedagogical treatment, and other factors (that are beyond the scope of this research) such as expectations, motivation, attitudes, etc.

Nevertheless, it is important to distinguish doubt about one's abilities or competence from doubt as a driving and supportive mechanism through which scientific understanding and scientific knowledge can be developed and acquired. The former can be assessed through standardized testing of self-esteem or self-worth in science. Such tests have showed, for example, that females usually get lower scores than males (Acker & Oatley, 1993; CCA/CCL, 2007; Thompson & Dinnel, 2007). It can also be assessed by allowing students the opportunity to freely express their inability to produce an answer to a question without penalty of any type. The latter, in which this research is interested, can occur when students have the opportunity to propose answers while also being given the possibility to express doubt about these answers. This particular form of doubt was studied by Merenluoto and Lehtinen (2002) in the field of mathematics education. These researchers concluded that performance and certainty usually go together, except for the students who perform best. For the latter, they found that certainty was almost as low as for the weakest performers. This led them to argue for the use of pedagogies that favour a tolerance for uncertainty. Personal doubt has also been studied by Hasan, Bagayoko and Kelley (1990), who used a 6-level scale (0 = totally guessed answer, 1 = almost a guess, 2 = not sure, 3 = sure, 4 = almost certain, 5 = certain) called the certainty of response index (CRI), and used it to measure doubt about expressed answers in order to distinguish between "lack of knowledge" and "misconceptions"; the former being given by wrong-and-doubted answers, and the latter by wrong-and-certain answers. Other research efforts in neurology (Burton, 2008; Koriat, 1993; Reder & Shunn, 1996), and psychology and evaluation (Gilles, 1997; Leclercq, Poumay, & Gagnayre, 2003), have showed that certainty of knowledge is often very different from evidence of knowledge and that certainty and doubt can have an important impact on further learning (e.g. René de Cotret and Larose (2007), who argued for the development of systematic vigilance toward one's own conceptions). According to Lee, Kwon, Park, and Kim (2003) (who developed a *degree-of-confidence* scale), doubt is also an important part of cognitive conflict, a step oftentimes presented as important in science learning (Dreyfus, Jungwirth, & Eliovitch, 1990; Hewson & Hewson, 1984; Limon, 2001; Nussbaum & Novick, 1982).

Although these research efforts have mainly concentrated on the diagnostics of what psychologists and neurologists refer to as the "feeling of knowing" (Burton, 2008; Koriat, 1993; Modirrousta & Fellows, 2008; Schnyder, Verfaellie, Alexander, & Lafleche, 2004) that comes with the production of answers, none (to our knowledge) have experimentally explored the effect of *initial* doubt and *initial* certainty (i.e. the state *preceding* a task) on science learning, even if this question has been presented many times as philosophically very important.

Doubt in different learning contexts

A consideration of the differences that can exist between different learning contexts, such as teaching-centered learning and problem-centered learning contexts, suggests that doubt will not be felt the same way in both. For example, teaching-centered learning, often presented as a "pedagogy of answers" (Astolfi, Darot, Ginsburger-Vogel, & Toussaint, 1997), often provides students with tools they need to resolve problems that "will be encountered only later" (p. 143). In turn, problem-centered learning, often presented as a "pedagogy of problems", usually presents as an "enigma" (p.144) or a puzzle that has to be solved through the discovery or the development of a solution. It can be reasonably hypothesized that doubt will not be experienced in the same fashion when students are being put in contact with answers relative to when they are exposed to an enigma. Furthermore, doubt in each context will likely not influence learning the same way. The present research aims to describe differences between the effects of initial doubt in the two contexts discussed above in light of the fundamentally different nature of each pedagogical treatment. The main research question explored through this research therefore relates to how initial certainty and doubt influence knowledge acquisition in the contexts of problem-centered learning and teaching-centered learning.

The exploratory nature of the research has lead us to consider two perspectives framing this question. The first focuses on the different categories of initial given answers, while the second focuses on students' certainty/doubt profiles, understood here as their general attitude of certainty toward a test, as indicated by the sum of certainty expressions (see methods section below).

We hope that answers to the aforementioned question will cast new light on what happens when problem-centered and teaching-centered approaches are used in a classroom context. We hope further that it will help increase understanding of which students might profit the most from the use of one pedagogical treatment over the other, and of how these influence the development of certainty/doubt toward knowledge.

METHODS

Instrument

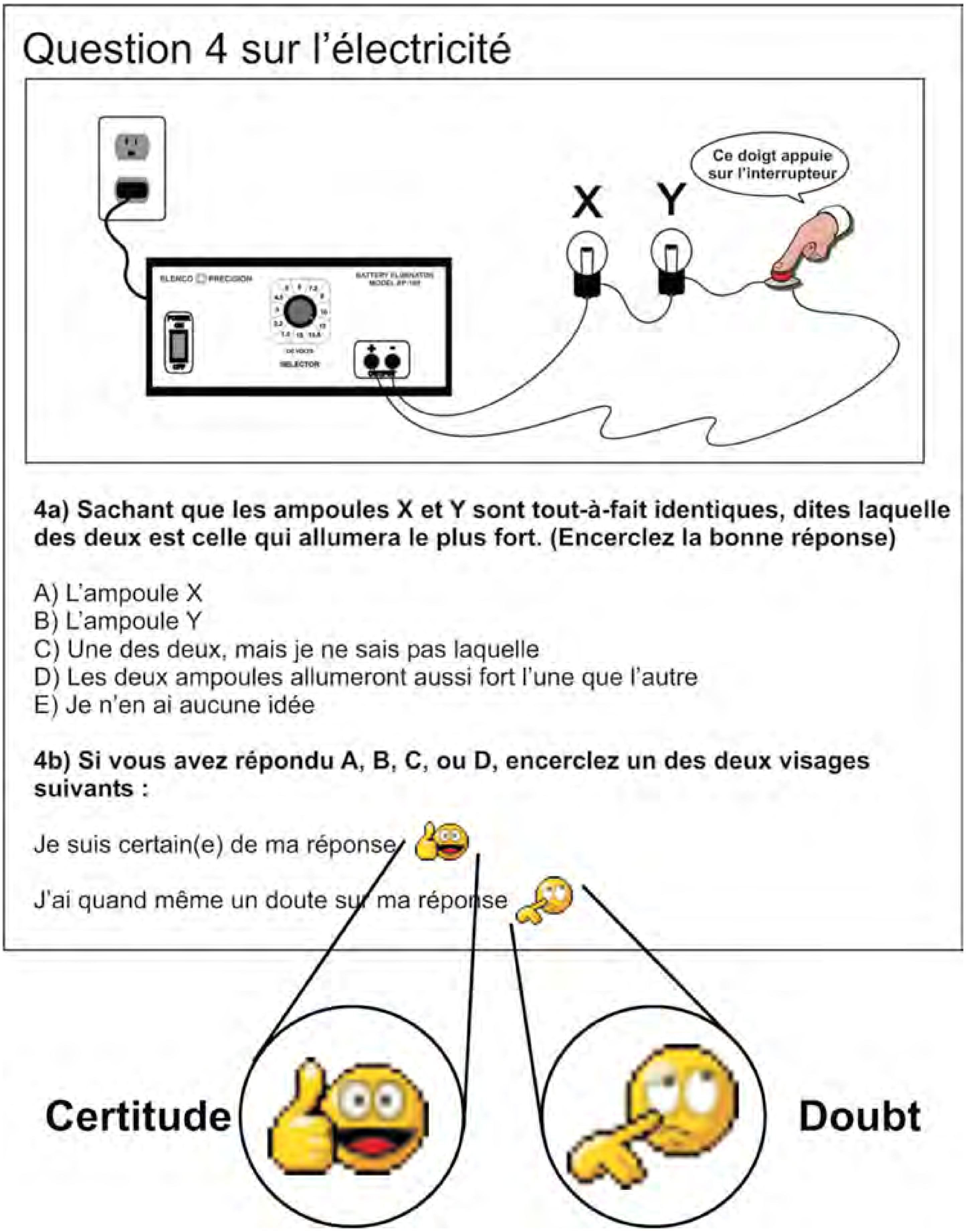
The pre-test (test) and post-test (retest) questionnaire were the same. They included eight multiple-choice questions (three to eight response choices per question) about simple electricity concepts. We chose to study learning about electricity because it is a typical topic addressed in Quebec's provincial curriculum, where the research was conducted. The questions evaluated the capacity of 13- to 15-year-old, French-speaking students to solve simple electricity comprehension problems often involving "unexpected conceptions" (Potvin, 2007). Unexpected conceptions are conceptions that are not expected from a pedagogical standpoint. They contradict the scientific content found in science textbooks.

The questionnaire synthesized many classical multiple choice questions available in the conceptual change literature regarding the learning of electricity (Chambers & Andre, 1997; Duit & von Rhoneck, 1998) and aimed to identify the following unexpected conceptions (among others):

- Q1) ***One wire is sufficient to light a bulb*** *(sink theory)* (Duit & von Rhoneck, 1998; Shipstone, 1984; Thouin, 2008).
- Q2) ***One of the poles (the positive one, most of the time) is a source or electrical current and the other "unloads" the « excess » and used current.***
- Q2) ***Two different currents collide in the bulb to light it*** *(clash theory* (Shipstone, 1984)).
- Q2 and Q3) ***It is not necessary for the current to go back to the source to light a bulb*** (Shipstone, 1984).
- Q4 and Q6) ***A bulb consumes current. A second one, wired in series with the first one, will therefore light less*** (Shipstone, 1984; Thouin, 2008).
- Q5) ***A node or a long wire are substantial obstacles to the circulation of current.***
- Q6 et Q7) ***Current distributes equally in parallel-connected wires.***

The pre-test was administered just before treatment and the post-test was given 25-30 days after treatment. Figure 1 offers an example of an item from the questionnaire.[1] In this question, students had to choose between: a) Bulb X; b) Bulb Y; c) One of the two; and d) Both will light up equally. For each question, students could also select a fifth option, namely e) I have no idea. If they tried another answer, they could also indicate whether they were "certain of their answer" or they "still had doubts" about it. For the purpose of the research, and even though we were aware that expressing uncertainty might be used by the students as a safety valve, we constructed doubt as being present when choosing to express some uncertainty while being certain enough to propose an answer.

FIGURE 1: A typical question of the test/retest



Question 4 sur l'électricité

4a) Sachant que les ampoules X et Y sont tout-à-fait identiques, dites laquelle des deux est celle qui allumera le plus fort. (Encerclez la bonne réponse)

A) L'ampoule X
B) L'ampoule Y
C) Une des deux, mais je ne sais pas laquelle
D) Les deux ampoules allumeront aussi fort l'une que l'autre
E) Je n'en ai aucune idée

4b) Si vous avez répondu A, B, C, ou D, encerclez un des deux visages suivants :

Je suis certain(e) de ma réponse

J'ai quand même un doute sur ma réponse

Participants

There were 251 secondary school students from eight classrooms who received treatment A (Group 1: problem-centered treatment) and 265 students from another eight classrooms who received treatment B (Group 2: teaching-centered treatment), for a total n=516 with an average of 27 students per classroom. These students came from 18 different schools and a total of 12 teachers were involved. Schools freely responded to an invitation to participate in the study made publicly on institutional websites. All those manifesting interest in the project were accepted. Each participating classroom was randomly assigned to one of the two treatments, forming groups 1 and 2. None of the students had prior formal training in problem-centered learning, nor in electricity—this topic being absent from previous curriculum—although we can assume that some of them had acquired some knowledge of the subject informally.

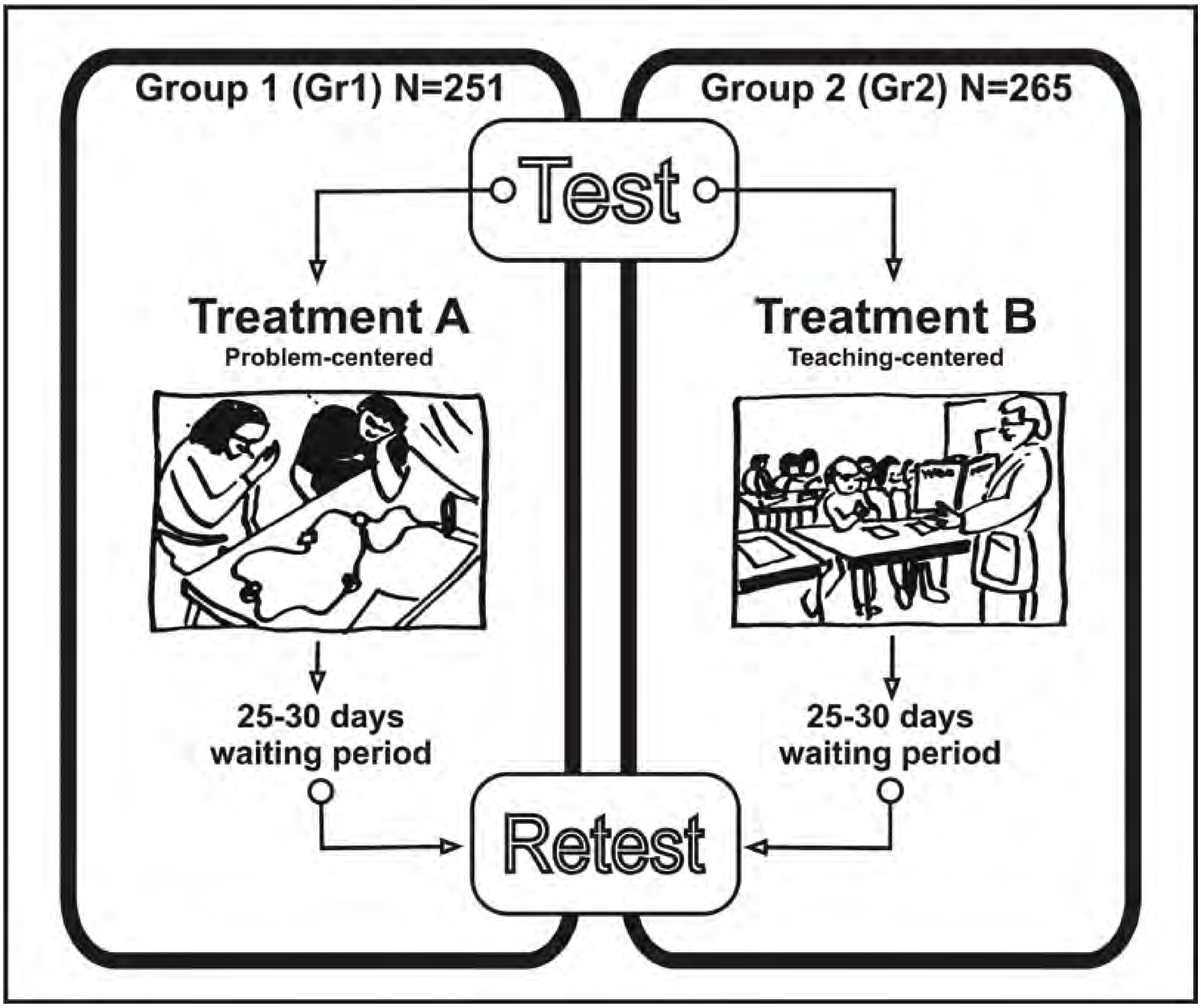
Treatment conditions

Treatment A was a problem-centered approach called "The Electrical Challenge", during which students had to solve, in lab conditions and with no help from their teacher, as many problems as they could in a 75-minute period. Twenty-four hands-on electrical problems or challenges classified from the simplest to the most complex were presented to students. These problems were all expressed in qualitative terms (ex: "Challenge No. 6: Switch A must light up bulb No.1 while switch B must light up bulb No. 2") and addressed electrical circulation, the effects of parallel and serial circuits, as well as the effects of electrical resistance. Students worked in pairs and had access to all available materials (electrical sources, wires, bulbs, resistors, etc.). Every time a team thought it had solved a problem, one of its members would raise his/her hand and a project assistant would confirm the solution by signing a form and allowing the team to move on to the next challenge/problem. This treatment can be considered as conforming to micro-PBL models where "PBL happens at a small scale, in a single course (50-180 minutes), where research of information is made on site […] by experiments, teamwork, using prior experience or logical reasoning" (free translation from Guilbert & Ouellet, 1997 p. 77).

Treatment B involved a teaching-centered approach, specifically a more typical science class featuring teacher-driven lessons, laboratories, textbook problems and exams that aimed at developing understanding of electricity concepts in the context of the usual secondary physics course. This treatment could be considered as an "explicit teaching" context (Bissonnette, Richard, & Gauthier, 2005) or "direct teaching" and was held within regular class activities. Hence, teachers were asked to teach as they normally would. Treatment B also devoted more time than treatment A to the study of the topic (several 75 minute periods). A total of six different teachers were involved in this treatment.

After the end of every treatment, a delay of 25 to 30 days was respected before administrating the retest. Teachers were asked not to discuss the topic for this period. We were aware that because of this delay the difference between test and retest would then be considerably reduced. However the durability of learning was considered important. We did not retest the students immediately after the treatment to avoid contamination of our delayed post-test (retest).

FIGURE 2: General organisation of the reserach



For the purpose of the analysis, we used a categorisation of answers inspired by earlier research like Merenluoto & Lentinen (2002) and Hasan *et al*. (1990), who used multiple-level certainty scales, but more closely by the work of Vachey (2001) who used a simpler categorisation that we deemed sufficient for our needs. These categories appear in the following table.

TABLE 1: Categories attributed to answers

Answer is…	Expressed doubt or certainty	Label given to the kind of answer
…right (1 point)	Certain about answer	Legitimate Certainty (LC)
…right (1 point)	Still has a doubt	Under-Estimation (UE)
…wrong (0 point)	Still has a doubt	Legitimate Doubt (LD)
…wrong (0 point)	Certain about answer	Over-Estimation (OE)
…unknown (0 point)	Does not apply	Do Not Know (DNK)

Two different analyses of the data were made. The first one focused on answers and their migration from one category to another, from testing to retesting, while the second focused on the students, their initial categorisation, and the migration of this category from test to retest. These two analyses were carried out for each of the two groups of students, allowing a comparison of the two pedagogical treatments. Calculations and commentaries about validity and reliability of the obtained data follow in the next section.

RESULTS AND ANALYSIS

Analysis of the initial answers and their migration

Tables 2 and 3 give the number of answers that went from one category to another for each one of the two groups. Each table gives the number of answers that belong to one category and ended in another. For example, the second column (the first one beginning with zero) indicates, for every questions and then for the total, how many answers were first given with legitimate certainty (i.e. in the pretest), and were later underestimated (i.e. in the post-test).

TABLE 2: Classification of the answers for treatment A (Group 1)

	Test for Group 1																								
	Legitimate Certainty					Under-Estimation					Legitimate Doubt					Over-Estimation					Do Not Know				
Retest for Group 1	Legitimate Certainty	Under-Estimation	Legitimate Doubt	Over-Estimation	Do Not Know	Legitimate Certainty	Under-Estimation	Legitimate Doubt	Over-Estimation	Do Not Know	Legitimate Certainty	Under-Estimation	Legitimate Doubt	Over-Estimation	Do Not Know	Legitimate Certainty	Under-Estimation	Legitimate Doubt	Over-Estimation	Do Not Know	Legitimate Certainty	Under-Estimation	Legitimate Doubt	Over-Estimation	Do Not Know
Q1	41	0	0	9	0	20	1	1	4	0	42	6	5	23	0	47	4	5	32	0	2	3	2	2	0
Q2	59	3	1	9	0	24	10	8	2	0	24	13	34	11	1	13	5	10	12	2	3	3	2	0	0
Q3	37	3	9	11	1	19	9	9	9	1	17	16	33	16	4	16	2	7	11	1	2	6	6	4	2
Q4	16	9	5	7	1	12	12	19	8	1	7	17	38	19	3	10	10	19	30	0	0	0	5	2	1
Q5	8	2	6	6	0	5	6	8	4	2	7	13	67	28	4	3	2	18	40	3	0	4	6	4	5
Q6	9	2	5	6	0	9	12	17	2	2	14	20	58	21	3	8	7	12	21	2	3	0	10	1	6
Q7	9	0	1	4	0	1	2	6	5	1	6	6	42	35	12	8	4	17	36	9	0	7	15	8	12
Q8	0	0	0	1	0	1	0	4	1	1	2	6	77	25	19	0	1	23	21	9	1	1	29	6	14
TOT	179	19	27	53	2	91	52	72	35	8	119	97	354	178	46	105	35	111	203	26	11	24	75	27	40

TABLE 3: Classification of the answers for treatment B (Group 2)

	Test for Group 2																								
	Legitimate Certainty					Under-Estimation					Legitimate Doubt					Over-Estimation					Do Not Know				
Retest for Group 2	Legitimate Certainty	Under-Estimation	Legitimate Doubt	Over-Estimation	Do Not Know	Legitimate Certainty	Under-Estimation	Legitimate Doubt	Over-Estimation	Do Not Know	Legitimate Certainty	Under-Estimation	Legitimate Doubt	Over-Estimation	Do Not Know	Legitimate Certainty	Under-Estimation	Legitimate Doubt	Over-Estimation	Do Not Know	Legitimate Certainty	Under-Estimation	Legitimate Doubt	Over-Estimation	Do Not Know
Q1	41	1	1	10	0	22	5	8	8	0	42	13	17	24	3	25	5	7	27	1	4	1	0	0	0
Q2	41	1	3	9	1	26	9	11	8	0	26	16	43	27	1	7	2	5	15	1	4	3	3	0	1
Q3	51	8	4	12	4	21	17	10	5	1	18	6	19	23	0	16	3	9	16	1	5	2	6	4	2
Q4	30	9	7	8	0	34	11	7	13	2	31	8	18	19	1	12	6	8	24	3	6	1	2	1	0
Q5	10	2	2	9	0	17	9	7	7	0	31	14	43	32	4	7	10	7	28	2	4	5	6	6	2
Q6	6	2	0	5	0	14	4	17	8	1	25	9	49	30	11	15	5	8	24	3	7	1	7	10	2
Q7	5	2	0	6	1	3	2	4	5	1	4	12	50	28	13	9	3	22	33	15	6	3	16	9	12
Q8	0	0	1	2	1	0	0	5	1	0	12	8	59	33	22	7	1	21	30	7	4	6	15	8	19
TOT	184	25	18	61	7	137	57	69	55	5	189	86	298	216	55	98	35	87	197	33	40	22	55	38	38

Figures 3 and 4 give a synthesized view of the percentage variation for each category for each of the two groups. Each grey area in the graph represents the evolution of a different category. Percentage variation for each category is also given. Increases in performance (% of right answers, including *legitimate certainty* (LC) and *underestimation* (UE)) and increases in certainty (% of certain answers, including *legitimate certainty* (LC) and *overestimation* (OE)) are given at the right.

FIGURE 3: Percentage variation of answers for each category of treatment A (Group 1)

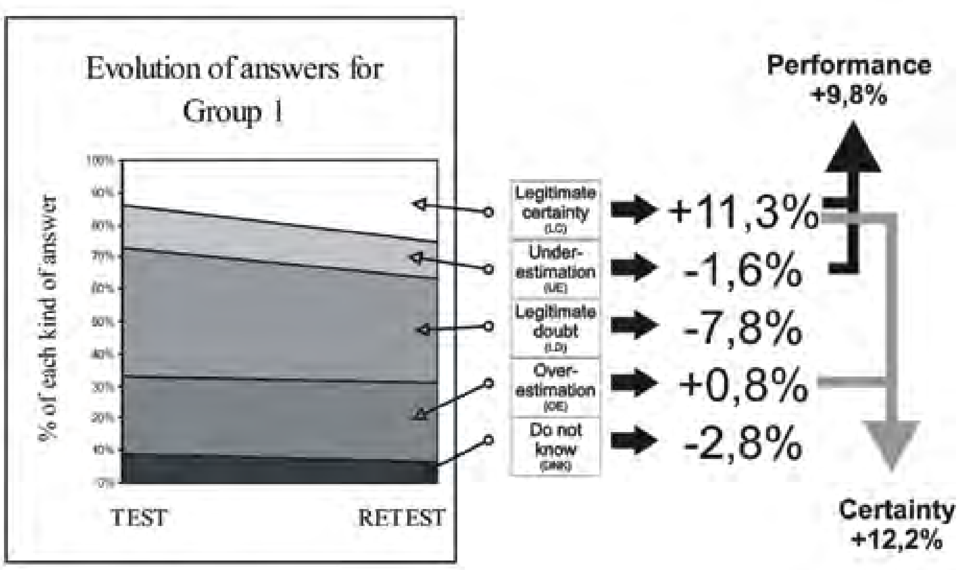
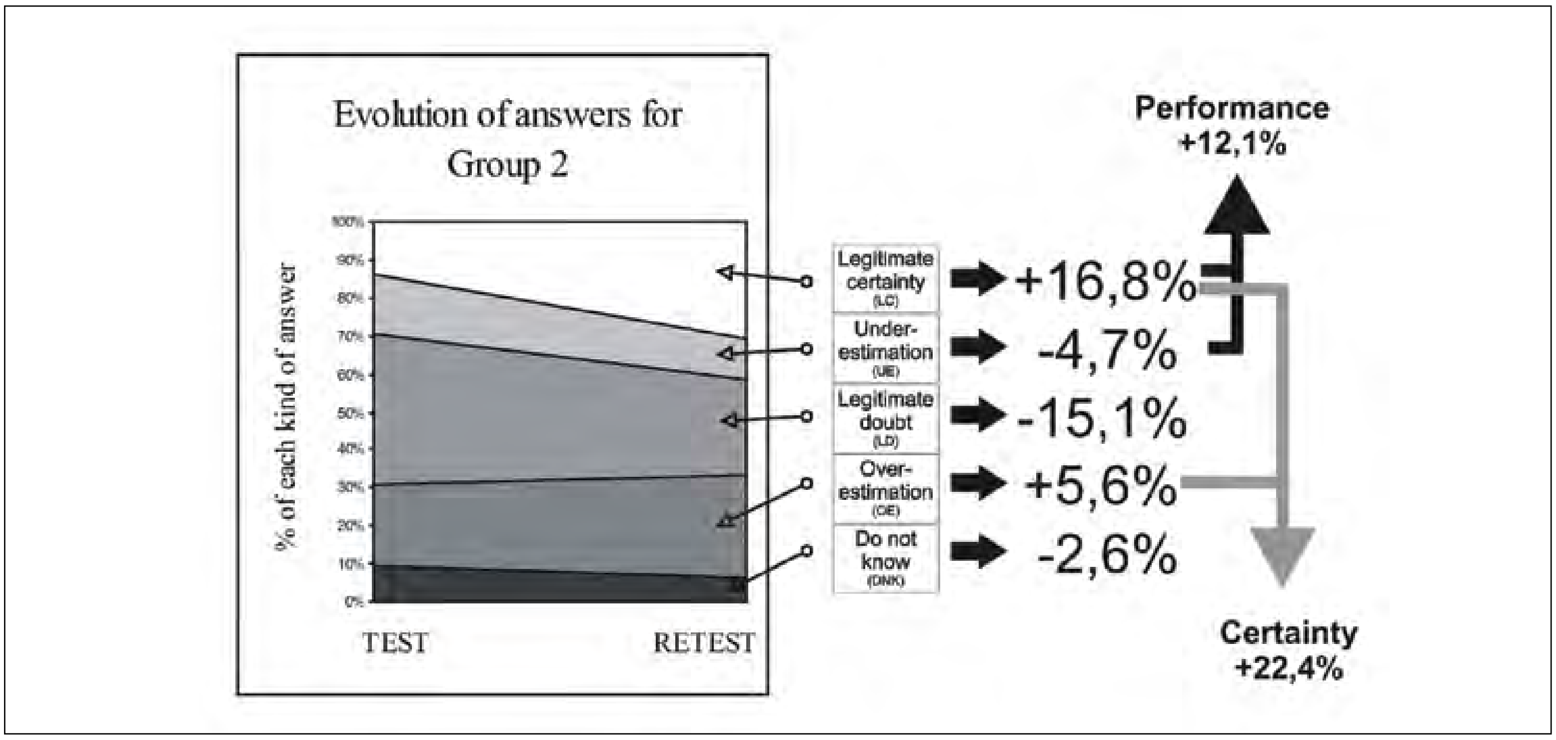


FIGURE 4: Percentage variation of answers for each category of treatment B (Group 2)



The first relevant observation we can make about the two treatments pertains to the important difference between the increase of *performance* (LC+UE) versus the increase of *certainty* (LC+OE). While the two treatments produced comparable increases in performance (9.8% and 12.1%), treatment B yielded a greater increase—almost double—in certainty than treatment A (22.4% vs. 12.2%). These results are very important because 1) they allow us to extend our comparison between the two treatments (increases in performance are comparable) and 2) they give an insight about the importance of doubt evolution between the two treatments.

The increase in certainty of Group 2 is manifested in both correct and incorrect answers. *Legitimate certainty* (LC) and *overestimation* (OE) are both about 5 points higher in Group 2 than in Group 1. This increase is compensated mostly by a decrease in *legitimate doubt* (LD) (-15.1% instead of -7.8% for Group 1) and to a smaller degree by a decrease in *under-estimation* (UE) (-4,7% instead of -1,6%). Moreover, a greater number of students in Group 2 were confirmed in their belief that their answers were correct (LC). However, a greater proportion of students from Group 2, relative to Group 1, also believed that their answers were correct when in fact they were not (OE). These findings may suggest that Group 2 students were less responsive to or influenced by the treatment to which they were exposed.

Figures 5 and 6 give a more detailed view of the migration of answers from one category to another, for both treatments A and B. In these figures, the reader's attention should be drawn to the arrows. For example, in figure 5, the arrow marked "3.6%" indicates that the balance of answers migrated from UE to LC. This does not signify that there was no migration from LC to UE, but rather that the overall migration was toward LC, in this particular proportion. The black arrows show the migrations from the *do not know* category (DNK) to each one of the other categories. The two bigger arrows depict general performance and general certainty. The absence of an arrow reveals a null balance. Moreover, all the arrows in these figures are depicted such that their surface is proportional to the balance of migrations.

FIGURE 5: Detailed migrations of answers for treatment A (Group 1)

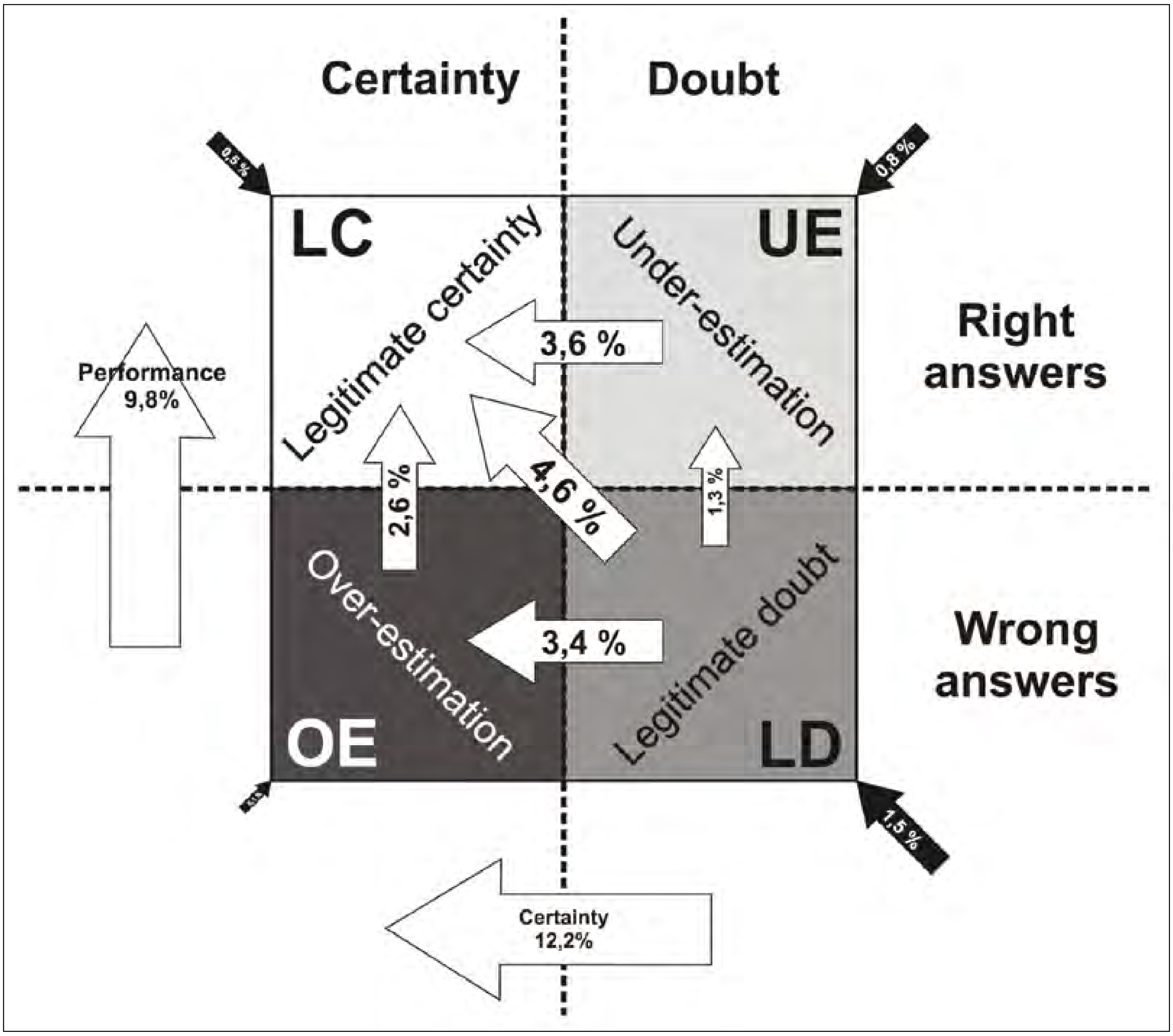
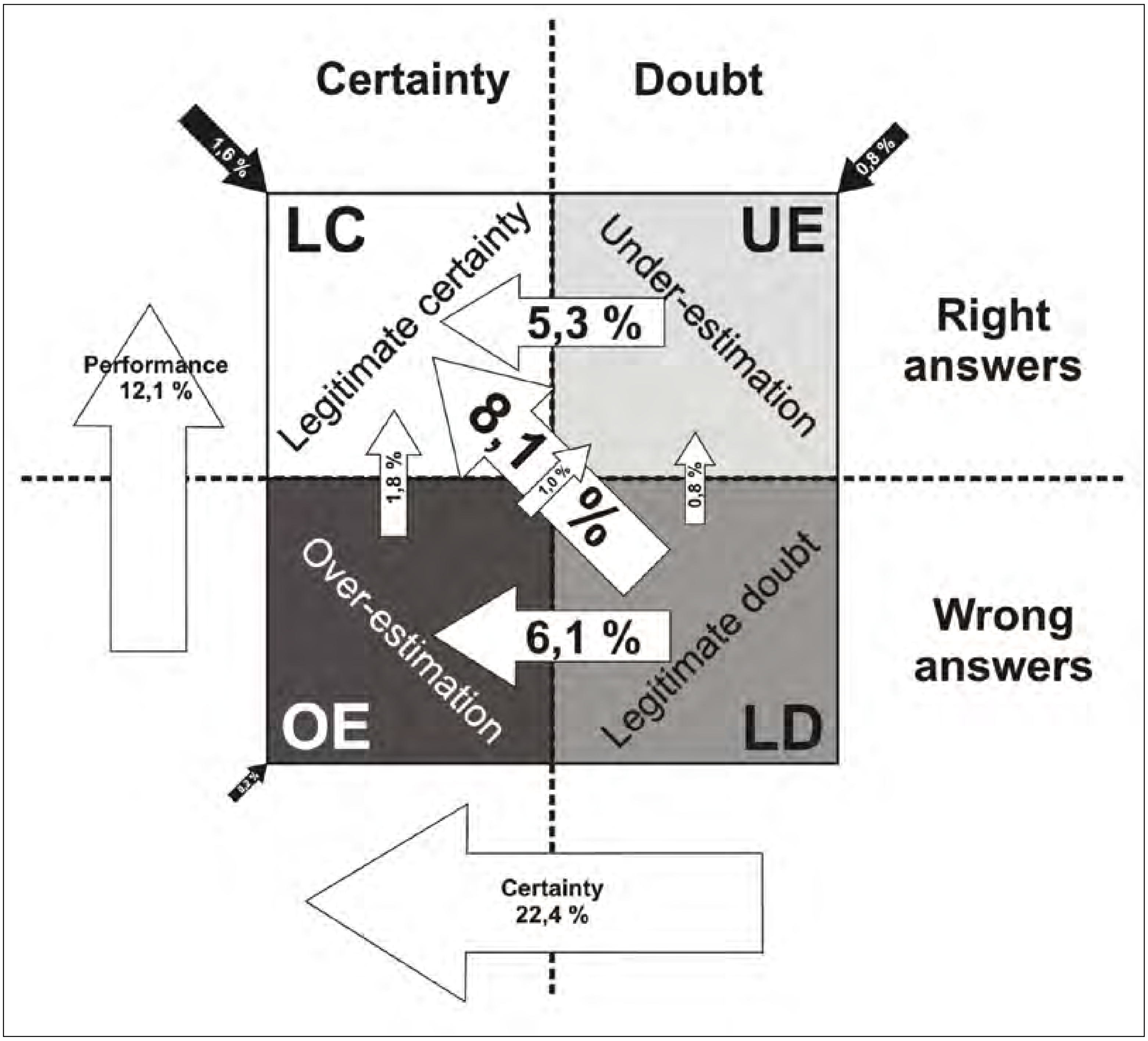


FIGURE 6: Detailed migrations of answers for treatment B (Group 2)



In addition to the observations already made about these figures, one can notice that the directions of the arrows are nearly identical from group 1 to group 2. The difference lies in the values associated with the migrations. For example, we notice that *do not know* (DNK) answers (black arrows) will migrate mainly to *legitimate doubt* (LD) for group 1 and to *legitimate certainty* (LC) for group 2, which is in line with earlier observations.

Moreover, the figures give an interesting overview of the general dynamics of doubt, that go mainly from legitimate doubt (LD) to overestimation (OE) (preferably) or underestimation (UE), and then to *legitimate certainty* (LC); or directly from legitimate doubt (LD) to legitimate certainty (LC). One can almost perceive a flux, from *legitimate doubt* to *legitimate certainty*, that seems to "prefer" passing through, in both cases, to *overestimation* rather than *under-estimation*.

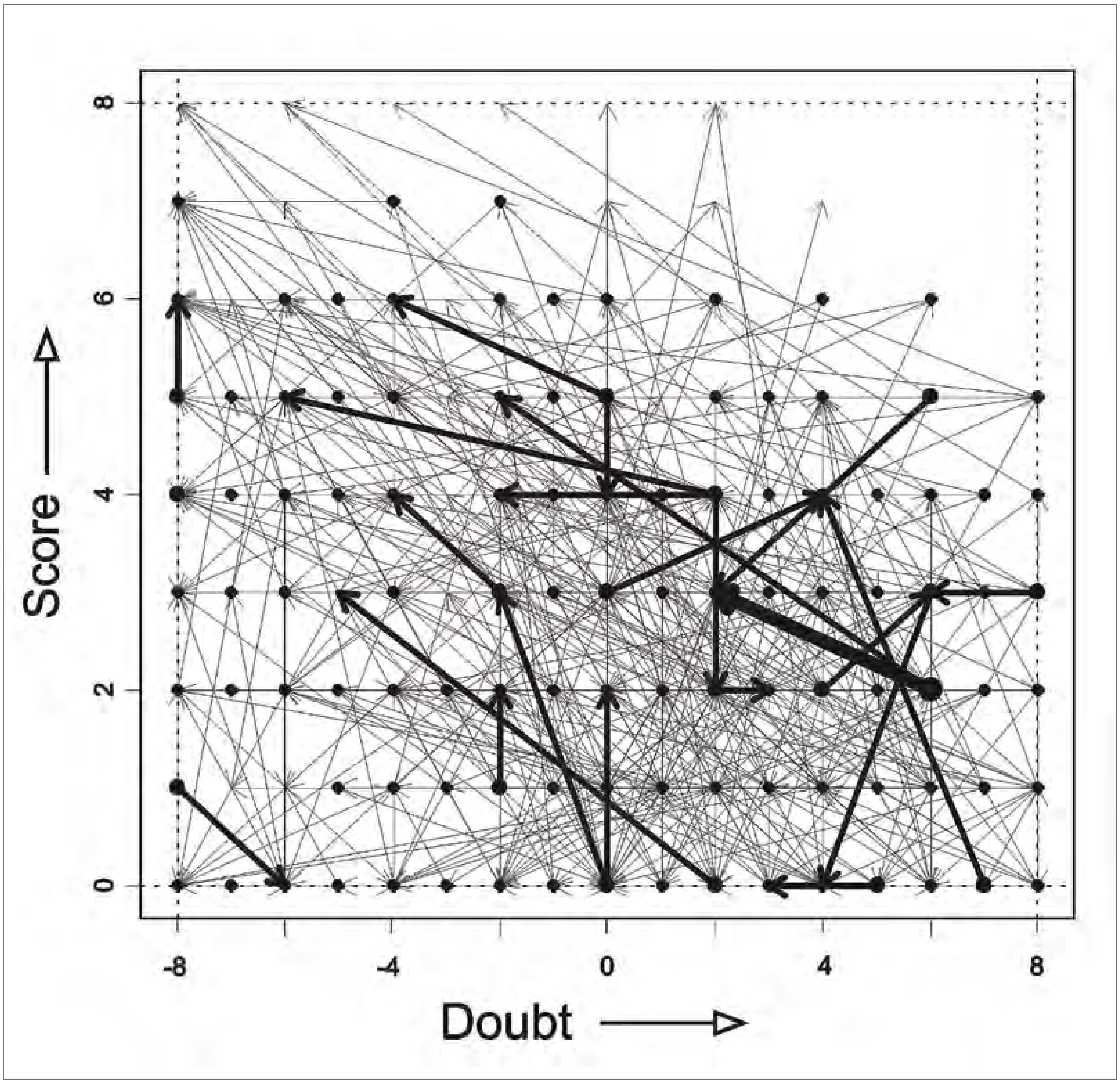
An interesting difference can be observed with regard to the total balance of answers labelled *overestimation* (OE). These answers could, as Hasan *et al*. (1990) suggested for wrong-and-sure answers, be a good indication of the presence of *misconceptions* (instead of simple lack of knowledge), so it is important to consider them. In Group 1, the total balance is almost null (3,4%-2,6%+0,1%=0,9%), and every migration out of this category is made toward legitimate certainty (LC). In Group 2, the migration to *overestimation* is clearly positive (6,1%-1,8%-1,0%+0,2%=3,5%) and answers sometimes migrate out to *under-estimation* (UE). These results are important because they suggest that treatment B might generate more misconceptions (positive migration balance) and that it might sometimes lead students to undervalue their progress (some migrations toward UE). This result is in line with Akinoglu and Tandogan's (2007) positive results about the prevention of misconceptions by problem-based active learning.

Another interesting observation we can make of this data is about the migration of answers out of *legitimate doubt* (LD). While migrations from this category to certainty (LC or OE) increase as much in Group 1 than in Group 2, migrations to *under-estimation* (UE) decrease. We can say about this interesting but difficult to interpret result, that it appears that traditional pedagogical treatments do not really encourage students to persist with doubting. We can also observe this while analysing the migrations in and out of *under-estimation*. While in-migrations are comparable for both groups, "out-migrations" mostly lead students to *legitimate certainty* (LC): this finding is also revealing because it suggests that traditional pedagogy seems to be more capable of renewing students' confidence in things they already know.

Analysis of students' attitudes and their migrations

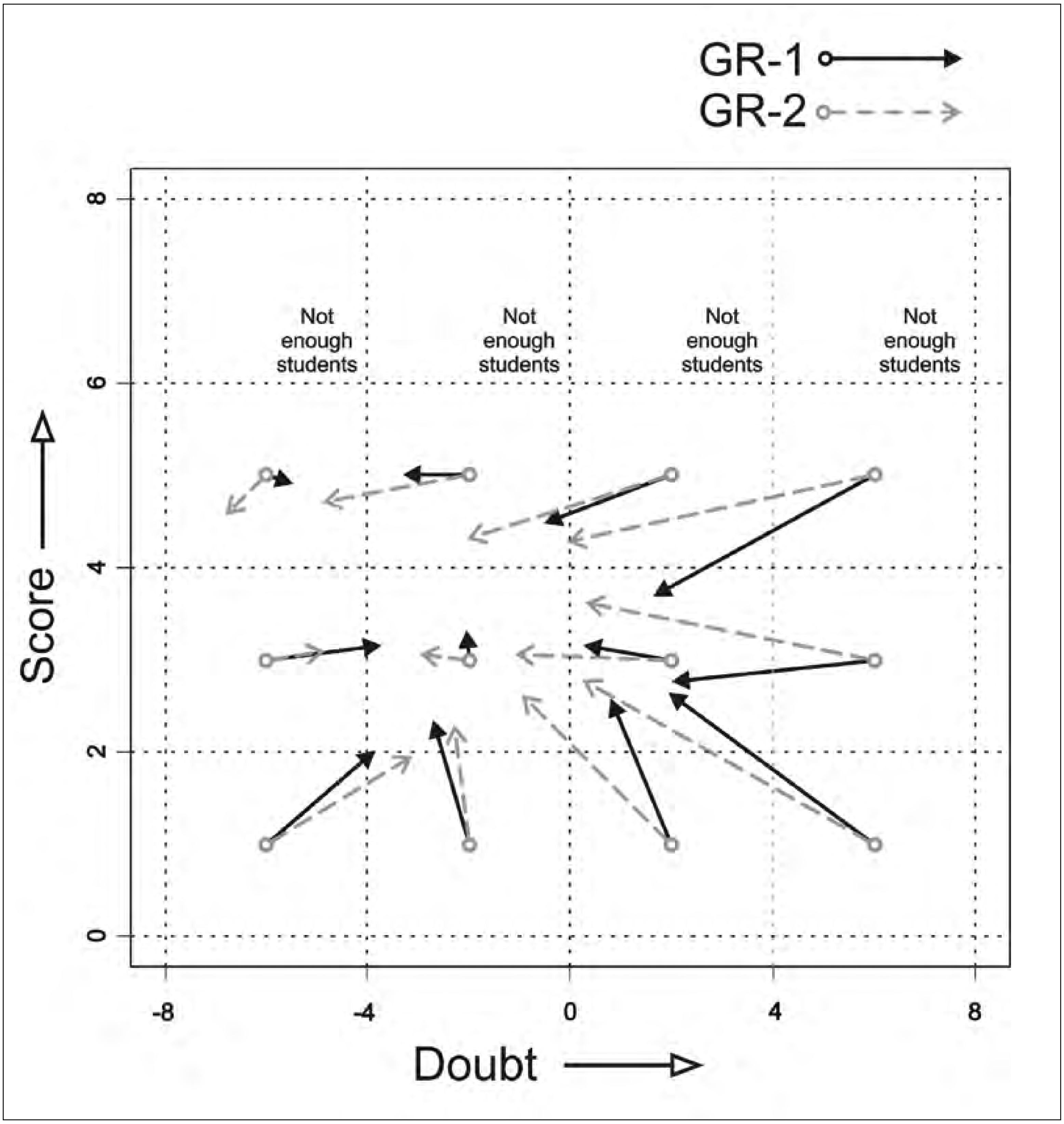
We now turn to a different analysis. Until now, it was difficult to understand the effects of the two treatments A and B on students' general "certainty/doubt" attitudes, because we analysed the questions separately and while not paying attention to individuals. We now consider the students' general initial attitudes toward performance and doubt, as well as the migration of these individuals from test to retest. Figure 7 gives an overview of all these migrations. The value on the X (doubt) axis was obtained by adding one point for every "doubt" answer given(LD or UE), and subtracting one point for every expressed certain answer (LC or OE). For example, using this technique, a student who expressed doubt as many times as he expressed certainty was assigned a score of 0, while a student expressing doubt for every answer would be assigned a score of -8. The value on the Y axis (score) was obtained by simply recording the scores. The tail of every vector marks the initial position for every student (score and general certainty) and the head marks the "retest position" of the same student. The width of vectors is proportional to superposition of arrows.

FIGURE 7: Migrations of all students from test to retest



Given the considerable difficulty of making sense of information as dense as that presented in this figure, we further refined the representation of these migrations. Figure 8 gives such a representation where vectors are regrouped in 16 areas given by initial test positions, and where resulting migrations (X and Y) are represented by a single vector, centered in the square. The zones containing too few vectors (less than 5) were not compiled. The linear vectors are the ones detailing migrations for Group 1 students, while the dotted ones represent migrations for Group 2.

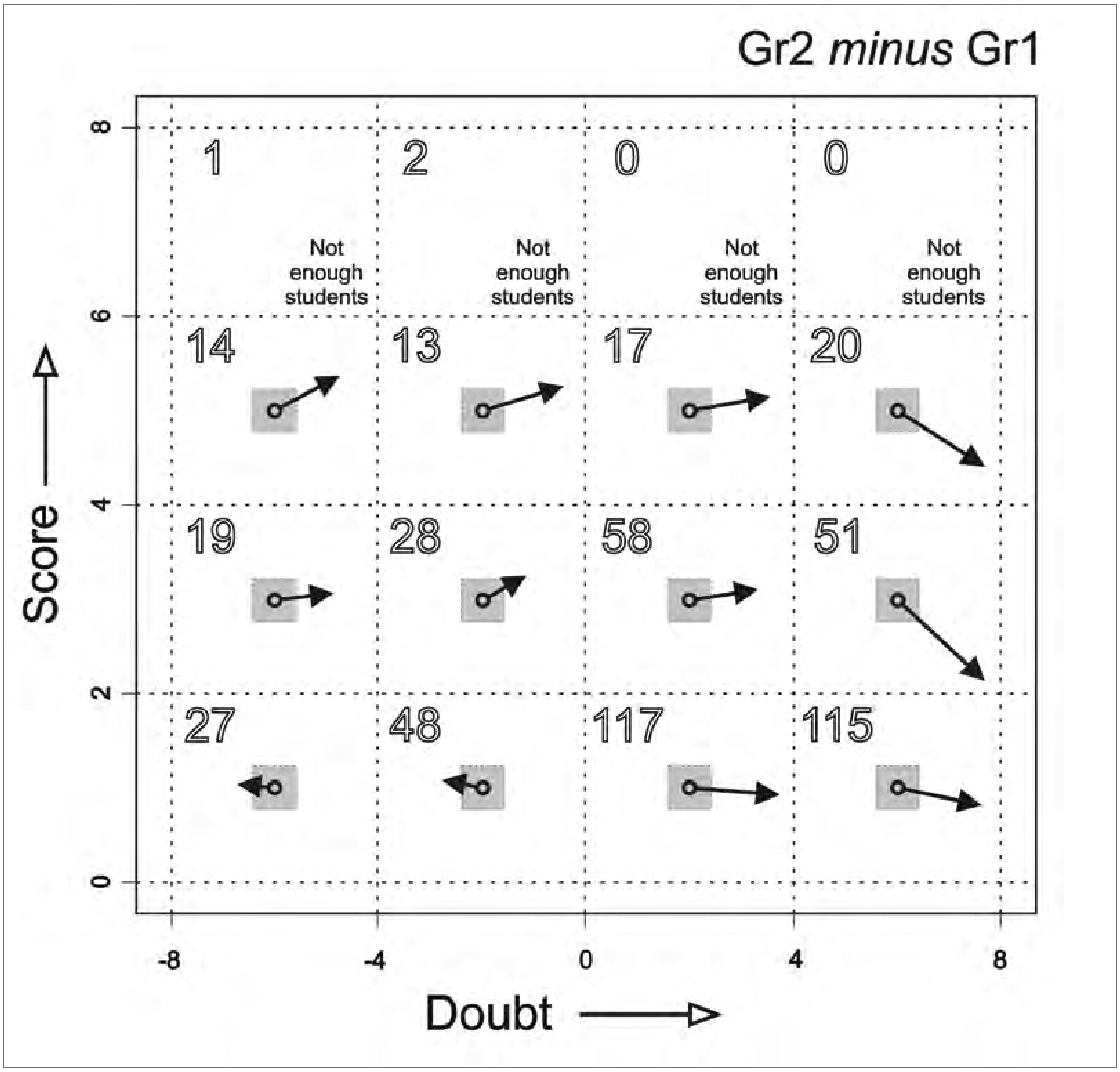
FIGURE 8: Resultants of student's migrations for both treatments A (Group 1) and B (Group 2)



Even with this refined representation, it is quite difficult to discern appreciable tendencies, especially when one considers how normal "edge effects" (an effect created by the impossibility for a value to be outside the matrix, thereby moving means away from the edges) seem to push the performance/doubt profiles toward the center of the figure. It is however still possible to observe that, surprisingly, students who show the best initial scores and more doubt (upper right) decrease considerably in performance while others generally increase. It would seem that an initial underestimating attitude is not the best one to expect effective learning in both treatments, and especially in treatment A (problem-centered).

A final and more interesting representation (see figure 9) can be produced data depicted from figure 8. To obtain it, we carried out a subtraction between vectors from groups 1 and vectors from group 2 (treatment B *minus* treatment A). Thus the arrows give an idea of the *difference* between the effects of the two treatments. The numbers in each box represent the total number of students considered in each subtraction. For example, the vector found in the lower right box was obtained by considering 115 student's migrations (initial and final "performance/doubt" profiles). It points toward the right indicating that doubt increased more (or was better preserved) in treatment A than in treatment B. It also slightly points down indicating that performance gain was less in treatment A. This new representation (figure 9) has the advantage of cancelling all edge effects (as these were present in both subtracted treatments), thereby revealing more about interesting differences. Grey areas or "boxes" give the standard error of measurement. The latter was obtained independently for both the X and Y axis by considering only the points for which the number of students was superior to 5. Boxes are of equal size because we have indicated only the most conservative one in every square. We can see that all migrations are larger than the standard error boxes. The shortest arrow is about 1.5 standard error and the longest is about 4 times the standard error. Assuming normal distributions, the probabilities that these results could be randomly generated are respectively below 14% and 1%.

FIGURE 9: Difference in student migrations between treatments A (Group 1) and B (Group 2)



A first observation can be made based on figure 9 about the general tendency for treatment A (a problem-centered approach) to better preserve doubt than treatment B (a teaching-centered approach) for most students, as revealed by most vectors heading toward the right in treatment A. We can see that students who combine poor initial performance and good certainty (lower left square, representing some 15% of students) would best preserve doubt if they were being taught in a traditional teaching-centered way (left pointing arrows). Interestingly, this conforms to interpretations made from preceding figures.

A second interesting observation is about students who were initially most uncertain about their answers (right column). It is quite striking to see that while almost every other group of students clearly benefited from the problem-centered approach (treatment A), the group of students whose initial uncertainty about their answers was highest did not seem to benefit at all, regardless of their initial performance. The difference here appears to be a question of "certainty/doubt" attitude. Many possible explanations might explain this finding. While it could be argued that the observations reflect the lack of familiarity of students for problem-centered approaches (treatment A), it could also be argued that uncertain students might not get as involved as they should in the teamwork required for problem solving, and that, therefore, they ultimately learned less. We could also argue that uncertain students might not be able to learn as much because they do not possess clear hypotheses on which they could build their comprehension and on which they could base their trial and error initiatives; or that they may not be able to find sufficient solid (scientific or not) grounds upon which to formulate or test hypotheses; etc. It would seem though that most students (a little less than two-thirds of them) are sufficiently certain of their proposed answers to attempt to test them in such a way that they can learn more from a "micro-problem-centered" approach (two-person teams). This is also an interesting result because it requires consideration of the importance of "dissatisfaction" (Strike, Posner, Hewson, & Gertzog, 1982) with one's own unexpected conceptions in the process of conceptual change. Our results (figure 9) seem to strengthen this claim because it is difficult to imagine how weakly endorsed conceptions could be associated with strong and clear dissatisfaction; conversely, it is easy to imagine higher levels of dissatisfaction when events confront conceptions deemed or felt to be certain.

An analogy involving a river and a waterfall may be useful in understanding the general dynamics of doubt illustrated in figure 9. A generally "beneficial" river of "problem-centered learning" flows from left to right but, at a certain point, the "waterfall of doubt" makes learning tumble down and leads to wasted effort. This suggests that when students feel most uncertain while engaged in problem-centered learning (or inquiry-based learning), a lecture at the right time may be beneficial, as Hmelo-Silver (2004) suggested. Although it is clear that we need more research on this, it seems that the provision by the teacher of at least a small number of knowledge elements that are presented as certain might from time to time be appropriate for further learning in such exploratory contexts.

A third observation concerns students who initially have the lowest performance (lower row). These students seem to be the ones for whom the difference in treatments has the smallest effect on performance. We can observe a very slight and not statistically significant advantage for the most confident of these students, but it would not be appropriate to draw further conclusions about this. We can also observe that, for such students taking part in the problem-centered treatment, confident students see their confidence grown while uncertain ones tend to become een more uncertain.

DISCUSSION

This research cannot draw conclusions about the general performance increases given by one or the other of our treatments because both treatments were not really comparable; for treatment B involved more teaching time with students). However, what does research does allow is for an important comparison of the dynamics of doubt with individual variations in performance, *notwithstanding the observation that general performance increases were comparable for both treatments*. It helps provide insight into what a teacher can expect to unfold following his decision to evolve from a "teacher-centered" practice toward a more "problem-centered" approach. The research thus suggests that such teachers should be alert to students who feel less certainty about their answers: they are the ones that are less susceptible to benefit from problem-centered teaching.

Our other main conclusions from this exploratory study are summarized next. It is very important to keep in mind that these conclusions can only be applied to the context of teaching physics and particularly electricity. Generalisation to other fields or other content would be unwarranted. Finally, considering the delay (25-30 days, with no mention of the topic) after which retest was administered, one should understand that our results are not meant to reflect immediate learning, but more appropriately mid-term learning.

- In problem-centered approaches, students might develop more doubt, or better preserve doubt (most of the time *legitimate doubt*) while learning, except for those students who combine very poor initial knowledge and very good certainty (in this study, they represented about 15% of the population studied). If we consider that doubt is an important part of science, this general result could be interpreted as a better conformity of problem-centered approaches to the conditions of real science. The observation that, in problem-centered approaches, doubt seems to accompany learning has been reported elsewhere. Galand and Frenay (2005), for example, have already recorded that students learning in these contexts feel they know less, while knowledge tests show that their knowledge is equal, if not superior, and that they have developed more competencies. We don't know if this situation (feeling doubtful despite actually knowing) is positively beneficial for learning, but our results suggest that while doubt seems to help learning in problem-based approaches, an excess of it might be harmful. Our results suggest that, when this happens, more traditional methods of teaching might be more appropriate, at least for a time.
- Students might develop fewer unexpected conceptions in problem-centered approaches. Since no content communication was made in treatment A, we could suppose that teachers or teacher-centered methods or tools used in this context could be responsible for the development of "misconceptions". We could also suppose that more conformity of our problem-centered treatment to real science could be an explanation. Being in direct contact with the reality of phenomena while learning could also improve conceptual change.
- About a third of the students in this study did not feel sufficiently certain of their initial conceptions to benefit from a problem-centered approach, while two-thirds did. Further research is required to determine if it could be possible to "boost" learner certainty before entering a problem-centered learning context, for example through classroom explanation of concepts, or by giving students the opportunity to have their ideas about a topic confronted to those of their peers.
- Students who present the poorest initial performance are not the ones who will benefit the most from a problem-centered approach. For them, the choice of treatment will make no measurable difference.

This research provided new insight into the application of problem-centered learning by using a perspective—the dynamics of doubt—that enabled further understanding of students' reactions toward different methods. We are, as a result, able to suggest that problem-centered approaches might be considered more interesting in cases where it is not possible to give differentiated pedagogical treatments in a class, because most of the students in this study seemed to benefit from such an approach.

The research also provided a good illustration that problem-centered approaches, given equal increases in performance, can better avoid the development of wrong-and-sure answers that we believe can be associated with unexpected conceptions.

CONCLUSION

This research allowed us to better understand the circumstances in which doubt plays a role in learning about electricity. Our results suggest the importance of considering general "doubt/certainty" attitudes in choosing the best pedagogical treatment for students. We believe our results reveal strengths, limits and a paradox in the use of these treatments.

First, students expressing certainty are the ones that benefited the most of the problem-based treatment, even when they were wrong about their initial answers (i.e. if they overestimated them). This might be a product of the use of "challenges" in this study, which we suggest may have given them the opportunity to confirm or invalidate initial hypotheses directly; in other words, to confront them with reality rather than simply with contradictory arguments. Two-thirds of these students seemed better prepared to benefit from the problem-based approach and developed less overestimated answers (less "misconceptions").

Second, it is possible that students who expressed more doubt underperformed in the problem-based treatment because they simply lacked solid hypotheses they could test themselves, or that they did not hold them strongly enough, even if these were right. For these students, is appears that teaching-centered approaches might be more beneficial for conceptual change and that providing them with knowledge presented validated by the scientific community might be a more suitable strategy. They also might benefit more from laboratory manipulations if hypotheses are simply given to them, such as in the teaching-centered approach.

As for doubt migration, it appears that, in problem-centered approaches, most students clearly moved toward doubt, but it seems that too strong a move toward a doubting disposition lead to a reduction in performance (cf. the "waterfall" metaphor discussed earlier, in relation to figure 9). The paradox is that, in our problem-centered approach, students who profited the most from the treatment were the ones who presented the highest level of certainty. Yet a problem-centred approach reduces certainty and therefore does not favour further learning. Meanwhile, in the teaching-centered approach, students seemed to develop certainty to the point that they appeared to have lost some of their capacity for reflection (see the analyses associated with figures 5 and 6) about what they learned (wrong-and-sure answers or unexpected conceptions), because they overestimated more often. One interesting interpretation from this research is that the best pedagogical strategy may be to avoid using only one or the other of the approaches described in this study, but rather to alternate them, even though such a strategy was not explicitly the object of this study.

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Authors' note

1 Item translation: "Knowing that X and Y bulbs are identical, identify the one that lights up the most (circle the right answer)".

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