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The relationships between the practice of different scientific activities and students' scientific knowledge, inquiry skills, view of the nature of science and attitude towards science: a study in primary school

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Abstract: Data from PISA and TIMSS have recently fuelled the debate on the efficacy of Inquiry-Based Science Teaching (IBST). Some analyses of these data show that the effects of different scientific activities related to IBST carried out with students vary according to the frequency of their implementation. Extending this research, the present study focuses on several scientific activities (Conception, Problem, Hypothesis, Model, Manipulation, Discussion-IBST, Interaction), some of which have not been considered previously. It investigates the extent to which these activities are implemented in teachers' practices and their relationships with student learning. The study is based on self-reported practices of primary school teachers in France (98) and data on their students (2250) measuring their scientific knowledge, inquiry skills, views of the nature of science (NOS) and attitudes towards science. Findings show that teachers' practices are diverse, with some teachers implementing scientific activities frequently and others rarely. However, no profile of teaching practices could be associated with high or low levels of student learning. The only scientific activity for which converging positive relationships with student learning were found was modelling. This finding calls for further studies to explore the relationships of the different modelling sub-practices with student learning.

Keywords: inquiry based science teaching, teachers' practices, students' learning

1. Introduction

The Programme for International Student Assessment (PISA) and Trends in International Mathematics and Science Study (TIMSS) surveys conducted in 2015 provided data not only on students' performance in science, but also on the teaching practices to which they were exposed. The various analyses of this data by researchers have revived the debate on the efficacy of inquiry-based science teaching (IBST). Some analyses suggest that IBST is correlated with greater student interest in science but poorer performance in terms of scientific knowledge and inquiry skills compared to teacher-directed instruction (Cairns & Areepattamannil, 2019; Forbes et al., 2020; Lau & Lam, 2017; Liou, 2021; Oliver et al., 2021; She, Lin & Huang, 2019). Other analyses qualify these results by pointing to the importance of teacher guidance: IBST with guidance is correlated with better performance in terms of scientific knowledge and inquiry skills (Aditomo & Klieme, 2020; Jerrim et al., 2019; Kang, 2022; Wang et al., 2022). This result corroborates previous research focusing on guidance (Alfieri et al. 2011; Furtak et al., 2012; Lazonder & Harmsen, 2016). Further analyses show that the relationship between the frequency of IBST and student performance is complex and overall non-linear: the more frequently IBST is practised, the higher student performance is, up to a certain frequency beyond which performance becomes lower again (Teig et al., 2018). Such a non-linear relationship also arises when considering in isolation some of the scientific activities that students may perform in IBST, such as conducting experiments or interpreting their results (Cairns, 2019; Oliver et al., 2021). These findings invite further consideration of the role of the various scientific activities. Some of them have not been considered in previous studies based on PISA and TIMSS 2015 data, such as the formulation of hypothesis or the construction, use and test of models, although they are essential components of scientific practices (Jiménez-Aleixandre & Crujeiras, 2017;

Schwarz et al., 2009; Windschitl et al., 2008). Therefore, there is a lack of data both on the frequency of the implementation of these activities in teachers' practices, but also on their effects on students. Further research is needed to determine precisely what each type of scientific activity is likely to provide for students, in terms of their learning of science, but also in terms of their understanding of the nature of science (NOS) and their interest in science.

The present study aims to investigate the frequency with which teachers implement different scientific activities, what profiles of science teaching practices can be inferred, and how these practices relate to students' learning in science. It is based on the reported practices of primary schools teachers in France, as well as on their students' performance in terms of knowledge and inquiry skills, their epistemic beliefs and their attitudes towards science.

2. Conceptual framework and empirical background

2.1 Definition of IBST and scientific activities

Definitions of IBST are varied and often not precise (Cairns & Areepattamannil, 2019). By crossing several conceptualisations of IBST (Aditomo & Klieme, 2020; Liou, 2021; Teig et al., 2018), we identified and chose the following minimal definition: in IBST, students are active and carry out scientific activities through which they construct scientific knowledge. In order to make this definition more explicit, several clarifications can be made. Students construct scientific knowledge based on their conceptions, which allow them to make sense of the phenomena studied (Anderson, 2007). Students are not only active at the manipulative level, but also and more importantly at the cognitive level (Mayer, 2009; Minner et al., 2010). Thus, they are responsible for scientific activities (Blanchard et al., 2010; Cairns & Areepattamannil, 2019; Teig et al., 2018). However, in

taking responsibility for scientific activities, students face the problem of cognitive load (Kirschner et al., 2006). Therefore, in IBST, the teacher can be responsible for certain activities (Blanchard et al., 2010) and can provide several degrees and forms of guidance (Lazonder & Harmsen, 2016).

What are the different scientific activities that might be implemented in the classroom as part of IBST? Through a systematic literature review, Pedaste et al. (2015) identified 34 activities classified into five phases of investigation: the Orientation phase with activities of exploring a phenomenon in order to stimulate curiosity about a topic and addressing a learning challenge through a problem statement; the Conceptualisation phase with activities of generating research questions and/or hypothesis based on the stated problem; the Investigation phase with activities of planning exploration or experimentation, collecting and analysing data, and interpreting data, possibly by means of models; the Conclusion phase consisting in drawing conclusions from the data; and the Discussion phase with activities of presenting findings or describing and discussing the inquiry phases.

What are the most appropriate scientific activities to implement in the classroom to promote student learning in science? This question implies first clarifying the objectives. In the IBST literature, the objectives put forward are most often to foster students' learning of scientific knowledge, the development of their inquiry skills and their view of NOS (Blanchard, 2010; Cairns, 2019; Kelly, 2014) and sometimes also to develop a positive attitude towards science (Aditomo & Klieme, 2020). To develop the whole range of inquiry skills and their NOS view that does not reduce science to a single scientific method focused on experimentation only, students may practice a diversity of scientific activities. The issue of acculturating students to the various scientific practices has been emphasised by science education researchers for a number of years (Jiménez-

Aleixandre & Crujeiras, 2017) and is reflected in policy documents such as the National Research Council framework in the US (NRC, 2012). This attention to scientific practices draws on work in the philosophy of science, which has been marked by a ‘practice turn’ (Soler et al., 2014) and has shed new light on NOS. In particular, this work has challenged an idealised view of experience that reduces its role to that of testing theory and has brought to the fore the long and complex processes of construction and negotiation that precede the stabilisation of knowledge. Accordingly, several activities considered essential in scientific practices and neglected in science education have been highlighted: identifying problems and framing questions (Blanchard et al., 2010; Osborne, 2014; Teig et al., 2018), constructing, using and testing models (Jiménez-Aleixandre & Crujeiras, 2017; Schwarz et al., 2009; Windschitl et al., 2008) and interacting by means of argumentation (Jiménez-Aleixandre & Crujeiras, 2017; Kuhn, 2017; Osborne, 2014). These same activities have also been stressed as important for fostering the learning of scientific knowledge (Kuhn, 2005; Windschitl et al., 2008).

2.2 Teachers’ practices and their effects on students

Are these different scientific activities implemented in the classroom by teachers, and how often? What are the effects of each of these scientific activities on students, on their learning of knowledge, the development of their inquiry skills, their view of NOS and their attitude towards science? The large-scale PISA and TIMSS assessments conducted in 2015 yielded a very large amount of data (from 72 and 39 countries respectively) making it possible to study students’ achievement in science (aged 15 and in grades 4 and 8 respectively) as a function of teaching practices measured by a set of items, some of which can be linked to IBST and specific scientific activities, and others to direct instruction. These data show that teachers’ practices are varied, in particular, they differ between schools but also between countries (Teig et al., 2022). The relationship between

these practices and student achievement turns out to be complex. According to the PISA 2015 data, the practices associated with better student achievement are not the same from one country to another (Forbes et al., 2020). Overall, a negative relationship appears to exist between the frequency of IBST implementation and student achievement, that measures both scientific knowledge and inquiry skills (Cairns & Areepattamannil, 2019; Lau & Lam, 2017; Liou, 2021). However, this relationship becomes positive if IBST implementation is combined with teacher guidance (Aditomo & Klieme, 2020; Jerrim et al., 2019; Kang, 2022; Wang et al., 2022). Guided IBST appears to be more effective in terms of student achievement than direct instruction, which in turn is more effective than unguided IBST. This finding corroborates previous research that has identified guidance as a critical variable (Alfieri et al. 2011; Furtak et al., 2012; Lazonder & Harmsen, 2016). An equivalent outcome was found with student NOS view as the target variable: unguided IBST is negatively correlated with the NOS view, while guided IBST is positively correlated with it (Aditomo & Klieme, 2020; Chi et al., 2021). As for the development of student attitude towards science, the data show an overall positive relationship with the frequency of IBST (Cairns & Areepattamannil, 2019; Liou, 2021). When considering the teacher guidance variable, it again appears to have a strong moderating effect: unguided IBST is either not significantly correlated or negatively correlated (depending on the country) with student attitudes towards science, while guided IBST is positively correlated with it (Aditomo & Klieme, 2020; Kang, 2022).

Besides, two studies have analysed separately the different scientific activities encapsulated in IBST as conceptualised by PISA, without distinguishing between the presence and absence of teacher guidance (Cairns, 2019; Oliver et al., 2021). The study covering all 69 countries in the survey (Cairns, 2019) shows negative relationship of several activities with science achievement (i.e., a steady decrease with frequency),

namely the activities in which: students are allowed to design their own experiments; there is a class debate about investigations; and students are asked to do an investigation to test ideas. In the case of two activities, the relationship with science achievement appears to be curvilinear (i.e., a maximum is reached when the activity is implemented in some lessons or most lessons), namely the activities in which: students are given opportunities to explain their ideas; students spend time in the laboratory doing practical experiments.

This last finding echoes the more general result found with the TIMSS 2015 data. A curvilinear relationship was exhibited between IBST, considered broadly, and student achievement in science (Teig et al., 2018). As the frequency of inquiry activities increased from low to medium values, student achievement increased until it reached an optimum value, and then at the highest frequency, student achievement decreased, meaning that the correlation became negative.

Furthermore, the PISA 2015 data show that, depending on the country, there are different patterns of IBST practices reported by the students with the highest average levels of science achievement (Forbes et al., 2020). In the case of France, together with Denmark, these students not only report the highest levels of IBST practices overall, but also disproportionately so for the specific practices of arguing about questions and drawing conclusions from evidence.

3. Rationale and research questions

PISA and TIMSS characterise IBST by considering only a limited number of scientific activities. In particular, neither of them takes into account the activity of generating hypotheses nor the activity of constructing, using, and evaluating models; the activity of formulating questions is omitted by PISA, while that of argumentation is omitted by

TIMSS (Teig et al., 2022). In this respect, the PISA and TIMSS surveys deserve to be extended by new studies considering other scientific activities, in particular those regarded as important both in the practices of scientists and in science learning. Moreover, these surveys only cover the secondary school level and leave the primary school level in the dark. These two issues motivate the present study which was conducted in the context of French primary schools and whose research questions are:

- RQ1: What are the science teaching practices at primary schools in France in terms of the frequency with which the different scientific activities related to IBST are carried out?
- RQ2: What are the links between the frequency of carrying out the different scientific activities related to IBST at primary schools in France and students' scientific knowledge, inquiry skills, NOS views, and attitudes towards science?

4. Methods

4.1 Participants

This study was conducted as part of the project [anonymized]. The participants in this study were 98 in-service primary school teachers in France and their students, i.e. 2250 students in grades 3 ($N = 553$), 4 ($N = 821$) and 5 ($N = 876$), aged 8–11. The teachers had an average age of 47.4 years ($SD = 7.6$), 70.1% were female, 43.4% had a university degree in science and an average of 16.0 years of experience in primary school ($SD = 8.34$).

4.2 Measures

The science teaching practices of these teachers were studied by means of a questionnaire (all items of this questionnaire are provided in the Supplemental Material A). The latter

consisted of nine close-ended questions on the frequency of implementation of different activities during the year in their class, with 4 frequency modalities (i.e., never/seldom, sometimes, often, always). All these activities are carried out by the students with more or less guidance from the teacher (which was not measured). Seven activities corresponded to scientific activities related to IBST: students express their conceptions of the phenomena under study and these conceptions are compared and discussed (Conception), students formulate a problem to be solved (Problem), students have to generate hypotheses to explain the phenomena under study (Hypothesis), students construct, use or test models (Model), students manipulate some instruments and materials to carry out an experiment or an observation (Manipulation), students discuss the phases of IBST that they have experienced or will experience (Discussion-IBST), and students interact within a group, possibly to cooperate, share their ideas and argue for them (Interaction). Two questions dealt with other science-related activities that are part of the French curriculum: students explore a socio-scientific issue, allowing them to discuss the links between science and society (Science&society), and students participate in activities related to sustainable development (Sustainable-development). Finally, a question was asked about the average number of hours spent on science in class per week (HoursOfScience), with the responses to this question recoded into three levels (few, medium, many).

On the students' side, questionnaires were administered to measure their scientific knowledge, inquiry skills, NOS view, and attitudes towards science (all items of these questionnaires are provided in the Supplemental Material B). To develop these questionnaires, we used questions from statistically validated standardised tests whenever possible (tests produced by science assessment institutions in various countries: USA, Australia, UK and Germany). With regard to students' scientific knowledge and inquiry

skills, we also drew on the extensive literature in science education on students' conceptions to develop original questions on specific topics when these conceptions were not addressed by standardised tests. The set of questions has been adapted to be consistent with the official French science curriculum for grades 3, 4 and 5. Concerning the NOS view, we have chosen points that are considered accessible to young students and that relate to both the nature of scientific knowledge and the nature of scientific practices, without distinguishing between the two (Bächtold et al., 2021), considering that these two aspects of science are intimately linked, in line with Clough (2011) and Hodson (2014). For attitudes towards science, the questions are adapted from those developed by Kind et al (2007).

For the first three measures, the questions were multiple choice, some common to all three grades, others specific (number of questions depending on grade level):

- scientific knowledge: 15–20 questions on different topics in the science curriculum (states of matter, energy, Earth-Sun system, electricity, mechanical systems, living/non-living, plants, animal reproduction, food chain, blood circulation, respiration). An example of an original question (i.e., developed by the research team of the project [anonymized]) relating to electrical circuits is given in Figure 1;
- inquiry skills: 7–8 questions on several inquiry phases (formulation of a scientific question, design of a controlled experiment, analysis and interpretation of data). See an example of question concerning the skill 'isolating variables', adapted from a standardised test (Project 2061 of the American Association for the Advancement of Science, USA16), in Figure 2;
- NOS view: 7–8 questions on the nature of scientific knowledge and the nature of scientific inquiry (the distinction between fact and opinion, the role of

experimental design, reproducibility of results, the role of models). An example of an original question on the role of experimental design is given in Figure 3.

For these three measures, a correct answer was coded as 1 and a wrong answer as 0. The mean scores were calculated for each student.

Figure 1. Example of a multiple choice question on scientific knowledge.

Figure 2. Example of a multiple choice question on inquiry skills.

Figure 3. Example of a multiple choice question on NOS view.

For attitudes towards science, 17 questions identical for the 3 grades were asked to the students who had to answer on a 5-point Likert scale (from ‘strongly agree’ to ‘strongly disagree’). These questions, inspired by Kind et al. (2007), fall under several dimensions combining intrinsic and extrinsic motivation and self-esteem (learning science at school, practical work in science, science outside school, importance of science, self-esteem in science, future participation in science). Figure 4 shows four examples of questions.

Figure 4. Examples of questions on students’ attitude towards science.

4.3 Data collection, validity and reliability of the student questionnaires

All questionnaire items were formulated in French. The items of the questionnaires designed for the students were first tested on the basis of semi-structured interviews with six students. This allowed to assess the understanding of the items and led to a slight rephrasing of some of them. Next they were tested with 500 students not involved in the main protocol (i.e., with the teachers of the study). This led to remove some items that were considered too complex and allowed to make a first assessment of validity (such as the one described below). The revised questionnaires were then administered at the end

of the schoolyear to all students included in the main protocol, 2250 of whom answered all questions. Surveyors were recruited and trained for this purpose. The time allowed to complete the questionnaires was limited to 45 min (with most students finishing before the end). They were completed on tablets, just like the questionnaire to be completed by their teachers at the same time. Prior to completing the questionnaire, all participants (i.e., teachers, students and their parents) provided informed consent in compliance with the European General Data Protection Regulation (EU) 2016/679.

The validity of the four student measures was assessed in three steps. First, content validity was assessed by the research team by comparing the content of the questions with the official French science curriculum for grades 3, 4 and 5. Second, a discriminative validity assessment was carried out on the data collected from the 2250 students. The means of the four student measures for grades 3, 4 and 5 were analysed (see Supplemental Material C) and compared with the literature. From grade 3 to grade 5, students' scientific knowledge, inquiry skills, and NOS view gradually increase, while their attitude towards science gradually decreases. The differences in means between grades 3 and 4 for these four measures are all significant; they are also significant between grades 4 and 5, except for attitude towards science. The increase in scientific knowledge and in NOS views and the decrease in attitude towards science are in line with the main trends found in previous studies, albeit with different grades (Lederman et al., 2021; Mullis et al., 2020; Potvin & Hasni, 2014). Third, a predictive validity assessment was performed on the same data. A linear regression model shows that scientific knowledge is predicted mainly by inquiry skills, then by NOS view, then by attitude towards science. The fact that the weight of NOS view in predicting scientific knowledge is higher than that of attitude towards science is consistent with previous studies (Guo et al., 2022; She et al., 2019).

Reliability analysis was carried out and yielded the McDonald's ω given in Table 1. Compared to Cronbach's α and other reliability measures, McDonald's ω has been shown to provide the most accurate correction of the attenuation of accidental deviations of observed scores from their true objective values (Revelle & Zinbarg, 2009). The ω value for attitude towards science was relatively high. The relatively low values for scientific knowledge and inquiry skills may be explained by the fact that the items assessed a variety of knowledge and skills, not all of which were necessarily covered by all students during the year of study. Low value for NOS view when conceptualised as epistemic beliefs and assessed by closed-ended questions is not unusual (DeBacker et al., 2008), especially in the case of primary students (supplementary materials of Schieffer et al., 2022), and can be explained by the fact that the epistemic beliefs of an individual might not form a coherent system (Schommer 1990).

Table 1. Reliability values (McDonald's omega) for the four student measures.

4.4 Analysis procedures

To combine the student data with the teacher practice data, the student scores on the 4 measures were partitioned for each grade into 4 levels (1 for low to 4 for high) which were then treated as equivalent regardless of the grade (e.g. a high knowledge score in grade 3 and a high knowledge score in grade 5 were classified in the same knowledge level).

The practice and student data were analysed using two multivariate statistical analysis methods: multiple correspondence factor analysis (MCA) (Greenacre and Blasius, 2006), performed with R software and the Factominer package, to identify correlations between different sets of variables; and implicative statistical analysis (ISA), performed with CHIC software, to detect implication links between different values of

variables (Gras et al., 1998). These two methods were chosen because they do not assume linear or even monotonic relationships between variables. Previous studies on the links between IBST practices and students' achievement have indeed highlighted relationships that may be curvilinear.

5. Results

5.1 Scientific activities in primary teachers practices

To investigate QR1, we first considered the frequency distribution for each scientific activity. All frequency distributions are found to have the approximate shape of a bell, with a maximum for either 'sometimes' (for Problem, Model, Discussion-IBST) or 'often' (for Conception, Hypothesis, Manipulation, Interaction) (see Figure 5). In other words, most teachers sometimes/often carry out these activities and fewer teachers always or never do so. Generating hypotheses is the most practised scientific activity among those considered in the study: 77.6 % of teachers either often or always implement it. Constructing, using or testing models is the least practised scientific activity: 79.6 % of teachers either never or sometimes implement it.

Figure 5. Frequency distributions of the scientific activities implemented by the 98 primary teachers in their classrooms.

Secondly, an MCA was performed to identify profiles of science teaching practices. Seven scientific activities (i.e. Conception, Problem, Hypothesis, Model, Manipulation, Discussion-IBST and Interaction) and two science-related activities (i.e. Science&society and Sustainable-Development) were considered as well as the average number of hours of science teaching per week. The different frequencies of these science teaching practices were taken as variables in the MCA. Four clusters could be distinguished: cluster 1 with 'always' for Hypothesis, Discussion-IBST and Problem, and

‘often’ for Model ($N = 41$); cluster 2 with ‘never’ for Model, and ‘often’ for Hypothesis and Problem ($N = 29$); cluster 3 with ‘never’ for Conceptions, and ‘sometimes’ for Hypothesis and Problem ($N = 4$); cluster 4 with ‘seldom’ for Manipulation, ‘sometimes’ for Hypothesis and Problem, and ‘never’ for Interaction ($N = 24$) (see Figure 6). These results show a diversity of practices, with some teachers often implementing scientific activities (cluster 1) and others rarely implementing them (cluster 4). These practice profiles are also differentiated by the average weekly time devoted to science, which is relatively high for teachers in cluster 1 and relatively low for those in cluster 4.

Figure 6. Clusters of science teaching practices derived from an MCA analysis. Four clusters are distinguished on this two-dimensional factorial map, each colour corresponding to a different cluster. The coloured dots represent the 98 teachers of the study.

5.2 Links between primary teachers’ practices and student measures

To explore RQ2, we combined the practice data with the student data. An MCA was first performed in two steps: using the four levels of the four student measures as variables to construct the dimensions of the model (step 1), and then adding the frequencies of the science teaching practices as supplementary variables (step 2). The results of Step 1 are displayed in Figure 7. They show strong correlations between high levels (i.e., level 4) of knowledge, inquiry skills and NOS view, the stronger correlations being between high levels of inquiry skills and NOS view. To a lesser extent, high levels of knowledge, inquiry skills and NOS view are correlated with high and rather high levels of attitude towards science. In a symmetrical manner, the results also show strong correlations between low levels (i.e., level 1) of knowledge, inquiry skills and NOS view, the stronger correlations being between low levels of inquiry skills and NOS view. A low level of attitude towards science shows its strongest correlation with a rather low level of

knowledge.

Figure 7. Correlations between the levels of student measures derived from an MCA analysis. Four measures are considered, each colour corresponding to a different student measure: scientific knowledge (here referred as Knowledge), inquiry skills (Skills), NOS views (NOS), and attitude towards science (Attitude). The different levels of students on these four measures, represented by discs, are the variables used to construct the axes of this two-dimensional factorial map. The distance between two discs represents the correlation between the corresponding variables (the smaller the distance, the higher the correlation). The size of the discs is related to the number of students.

The results of Step 2 are presented in Figure 8. They show negligible correlations between the frequencies of the different teaching practices, including the seven scientific activities, and the levels of student measures. Each frequency of each scientific activity is as weakly correlated with the highest levels of knowledge, inquiry skills, NOS view and attitude towards science as it is with their lowest levels. This result implies that it is not possible to identify practice profiles (i.e., clusters of practices characterised by certain frequencies of certain scientific activities) associated with either higher or lower levels of student measures.

Figure 8. Correlations between the frequencies of the different science teaching practices and the levels of student measures derived from an MCA analysis. This graph is identical to the one in Figure 6, except that the frequencies of the different teaching practices have been added as supplementary variables (i.e. they do not contribute to the construction of the axes). Each red cross represents a given frequency of a certain teaching practice. To avoid making the graph unreadable, the labels associated to these crosses are not shown, except for the two crosses which are slightly off-centre. The graph shows that all the red crosses are concentrated in the middle of the factorial map, which means that the frequencies of the different teaching practices are very weakly correlated with the levels of the student measures.

Secondly, an ISA was performed to analyse the implication links between all

variables related to scientific activities and all variables related to student measures, and thereby to identify possible local links between a given scientific activity and a given student measure. Three thresholds of implication intensity were considered: 75, 85, and 95 (50 corresponding to full randomness and 100 to absolute implication). 92 implications with an intensity above one of these thresholds were found as shown in Figure 9. Among them, 46 implications show a relationship between a certain frequency of one scientific activity and a certain frequency of another scientific activity (e.g. never constructing, using and testing models implies seldom expressing, comparing and discussing students' conceptions), 16 implications show a relationship between a certain level of one student measure and a certain level of another student measure (e.g. a high level of knowledge implies a high level of NOS view), and 30 implications show a relationship between a certain frequency of one scientific activity and a certain level of one student measure. We have analysed the latter set of implications in more detail. This analysis led to the identification of some implications that contradict the assumption of monotonic relationships, in that the lowest or highest levels (i.e., 1 or 4) of some student measures are implied or imply intermediate frequencies (i.e., 'sometimes' or 'often') of some scientific activities. For instance, the lowest level of attitude towards science implies the practice of sometimes generating hypotheses and also the practice of often formulating and solving a problem. This analysis also led to the identification of an effective practice: two implications are pointing to a positive relationship between the frequency of the practice of constructing, using and testing models and student measures: {Model *never*} is implied by {NOS view *level 1*} with an intensity of 88, and {Model *often*} is implied by {knowledge *level 4*} with an intensity of 89. It is important to stress that 'often' is the highest frequency of modelling practice reported by teachers (see Figure 5).

Figure 9. Implication relations between the frequencies of the different science teaching practices and the levels of student measures derived from an ISA analysis. The arrows represent implications that are above a certain threshold value. Each arrow colour corresponds to a different threshold value: 75 (grey), 85 (green), 95 (blue), 99 (red).

6. Discussion

There are several limitations to these findings. The teaching practices taken into account are those declared by the teachers and not those observed in actual situations. These practices were characterised without distinguishing between the topics covered. Nor have they been differentiated by including the more or less important guidance given by teachers, although the literature points to the crucial role of this guidance. The questions on the various scientific activities were relatively short and did not always include examples, even though they dealt with sometimes complex notions (e.g. conception and hypothesis), which may have made it difficult for some teachers to answer. Besides, the students' data may depend on the teaching they received in previous years from other teachers and therefore possibly with other teaching practices. Finally, the data were limited to the case of France. These limitations call for some caution in the conclusions we are going to propose.

The first aim of this study was to characterise the practices of in-service primary teachers and to determine to what extent these teachers implement in their classrooms the different scientific activities related to IBST (RQ1). The study is based on the responses of 98 French teachers to a questionnaire about their science teaching practices. The findings show that most French primary teachers 'sometimes' carry out scientific activities consisting of formulating and solving a problem, constructing, using or testing models and discussing the phases of IBST, and 'often' carry out scientific activities consisting of comparing conceptions, generating hypotheses, manipulating and interacting in a group. It should be noted that these results may not be the same in other

countries. Indeed analysis of the PISA 2015 data with 15-year-old students shows significant differences between countries regarding the frequency with which different scientific activities are practised (Forbes et al., 2020). The data of the present study show in particular that the construction, use or test of models is a scientific activity that is relatively rarely practised. This result is consistent with a study according to which primary school teachers in Germany and the United States offer their students very few opportunities for scientific modelling practices (Böschl et al., 2023).

The clustering analysis revealed contrasting profiles of science teaching practices in primary schools. In particular, two contrasting profiles emerged: the first corresponded to a relatively high level of practice of several scientific activities and a relatively high amount of time devoted to science, while the second corresponded to a relatively low level of practice of several scientific activities and a relatively low amount of time devoted to science. This result suggests a large inter-individual variability in teaching practices, beyond the differences in practice between countries or between schools (Teig et al., 2022).

The second aim of this study was to investigate the links between different science teaching practices and students' scientific knowledge, inquiry skills, NOS views, and attitudes towards science (RQ2). The MCA analysis shows that the frequency of practice of the various scientific activities is not significantly correlated with the overall level of the students. This means that the data do not allow for the identification of profiles of science teaching practices that are associated with high or low levels of student learning in terms of scientific knowledge, inquiry skills, NOS views, and attitudes towards science.

However, thanks to the ISA analysis, it was possible to identify localised relationships between some frequencies of scientific activities and some levels of student measures. The links of implication are not strong enough to constitute complete curves

which would show how the level of students on a given measure evolves as a function of the frequency of practice of a scientific activity. Nevertheless, some of the implications found, although isolated (i.e., for particular frequencies and for particular levels of student), mean that the hypothesis of a monotonic relationship should be rejected in this case. These implications show that the minimum/maximum found for the level of students on a given measure does not correspond to the minimum/maximum frequency of the practice of a scientific activity (e.g., the lowest level of attitude towards science is related to the practice of sometimes generating hypotheses, not never/always).

These results for primary schools are in line with those obtained for middle schools based on data from PISA and TIMSS 2015. From the latter data, a curvilinear relationship was derived between IBST practice and student achievement in science: for low and medium values, the frequency of scientific activities (without distinguishing their nature) is positively correlated with student achievement, but for higher values, the correlation becomes negative (Teig et al., 2018). Such a curvilinear relationship was found more specifically for certain scientific activities, for example students spend time in the laboratory doing practical experiments (Cairns, 2019; Oliver et al., 2021).

The convergence of these results for primary and middle school invites us to draw a balanced conclusion about the efficacy of IBST and, more generally, about the approach to be favoured for teaching science. Data from PISA and TIMSS 2015 have recently revived the debate as to whether or not IBST is more effective than direct instruction (i.e., where the teacher directly transmits scientific knowledge). If IBST is considered in a non-differentiated way and the question is asked in a binary way (i.e., for or against IBST), the evidence argues against IBST and in favour of direct instruction (Cairns & Areepattamannil, 2019; Lau & Lam, 2017; Liou, 2021). If IBST is considered by integrating the issue of guidance, the conclusion is more qualified: IBST without

guidance is less effective than direct instruction, but with guidance it is more effective (Aditomo & Klieme, 2020; Jerrim et al., 2019; Kang, 2022; Wang et al., 2022). This conclusion has been challenged by some researchers who point out that the guidance items actually describe teacher transmission of science content (Zhang & Cobern, 2021) and that, in the end, the results imply that direct instruction is more effective than IBST (Zhang et al., 2022). However, as stressed by de Jong et al. (2023), the latter conclusion ignores meta-analyses of previous studies, in particular one (Minner et al., 2010) based on 138 studies on the effectiveness of IBST, which have consistently shown that teaching approaches that include inquiry-based learning are more effective than direct instruction. Furthermore, it ignores the curvilinear relationships from the PISA and TIMSS 2015 data, which suggest that a combination of IBST and direct instruction may be the most effective approach to favour student learning (Jong et al., 2023). The findings of the present study support this more qualified conclusion. According to these findings, students' highest levels of scientific knowledge, inquiry skills, NOS views, and attitudes towards science are correlated with neither the lowest nor the highest frequencies of the different scientific activities considered. The relevance of engaging students in scientific activities in the classroom may depend on the nature of the topic. As suggested by de Jong et al. (2023), scientific activities are likely to be appropriate for dealing in depth with content that is open to multiple interpretations or misconceptions. In contrast, content that is more factual or easy to understand may be better suited to direct instruction. Furthermore, the practice of scientific activities and direct instruction, when combined, can be mutually beneficial: if direct instruction precedes scientific activities, it can provide students with the necessary prior knowledge, and conversely, scientific activities can foster a readiness to learn from direct instruction (Jong et al., 2023).

The results of the present study are different for one scientific activity: there is converging evidence towards a positive relationship between the frequency of constructing, using or testing models and student measures. More precisely, according to the ISA analysis, the absence of modelling practice is linked to the lowest level of student learning in terms of NOS view, and frequent modelling practice is linked to the highest level of student learning in terms of scientific knowledge. It should be emphasised that the significant relationships are only partial and do not enable us to reconstruct a complete curve showing a monotonic relationship between modelling practice and NOS view or scientific knowledge. However, no relationship was found in favour of a curvilinear pattern. The results are more positive for this scientific activity than for all the others considered in this study.

One possible explanation for the finding that modelling practice in the classroom would favour a more elaborate NOS view is that the activity of constructing models and confronting them with experience is a core scientific practice (Jiménez-Aleixandre & Crujeiras, 2017; Schwarz et al., 2009; Windschitl et al., 2008). The majority of students, at all grades, see models as idealised representations of the reality under study with the role of describing it, and tend to ignore the fact that predictions can be derived from models, and that these can thus be tested by experiments (Gogolin & Krüger, 2018). This activity of testing a model is very rarely implemented with primary school students, as is the activity of revising a model (Böschl et al., 2023). Giving students more opportunities to carry out such activities with models may be an effective way of developing their NOS view.

The result suggesting that modelling practice promotes the learning of scientific knowledge might be explained by the essential cognitive activities that the construction of models and their confrontation with experience make possible, such as analyzing,

reasoning, synthesizing, quantifying, explaining, arguing and evaluating (Louca & Zacharia, 2015). The construction of a model requires students to analyse the phenomenon under study, identify key elements, and reason on the possible relations between them (Mulder, Lazonder & de Jong, 2015). Confronting a model with experience provides students opportunity to get a feedback on the correctness of their model (Mulder, Lazonder & de Jong, 2015), and to argue for or against the model (Louca & Zacharia, 2015). Accordingly, modelling practice allows them to revise their own conceptual models (Schwarz et al., 2009).

7. Future directions of research

The scientific activity of constructing, using and testing models has not been studied in the PISA and TIMSS 2015 surveys. The results of the present study are therefore original. However, they need to be confirmed and refined by further studies. In particular, the links between this scientific activity and the student measures could be explored in other countries and at secondary school level. In view of the above-mentioned limitations of the present study, other directions of research could also be developed. In order to measure more precisely the effects of the implementation of different scientific activities in the classroom on student measures, teachers' practices could be characterised more finely: by distinguishing the topics on which these practices focus (e.g. states of matter, energy, electricity, animal reproduction, food chain or blood circulation), by integrating the degree of teacher guidance (e.g. none, low, medium and high) and by differentiating certain sub-practices associated with the scientific activities (e.g. by considering separately the construction, use, evaluation and revision of models, following the distinction made by Schwarz et al., 2009). These distinctions could be incorporated into large-scale studies implemented in different countries (such as PISA and TIMSS), at both primary and secondary school level.

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Ethics statement

The ethics processes followed in this study were approved by the Institutional Review Board of Paris School of Economics (Number [IN/2005009]).

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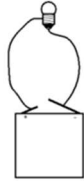
Table 1. Reliability values (McDonald's omega) for the four student measures.

	McDonald's ω		
	Grade 3	Grade 4	Grade 5
Scientific knowledge	.605	.719	.643
Inquiry skills	.544	.490	.513
NOS view	.651	.520	.574
	Grades 3, 4 and 5		
Attitude towards science	.865		

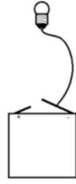
Figure 1. Example of a multiple choice question on scientific knowledge.

Below are four suggested electrical arrangements using a battery, a light bulb, and electrical wires. Which set-up will light the bulb?

A



B



C



D



Figure 2. Example of a multiple choice question on inquiry skills.

A friend wants to do an experiment to test an idea. The idea is that the heavier a car is, the faster it will go down a ramp. To do this, your friend can change the weight of the car by adding balls (one ball, two balls or three balls) and he can also change the height of the ramp by adding blocks (1 block, 2 blocks or 3 blocks). To test his idea, your friend has to decide between these four possibilities. What would you advise him to choose between solutions A, B, C or D?

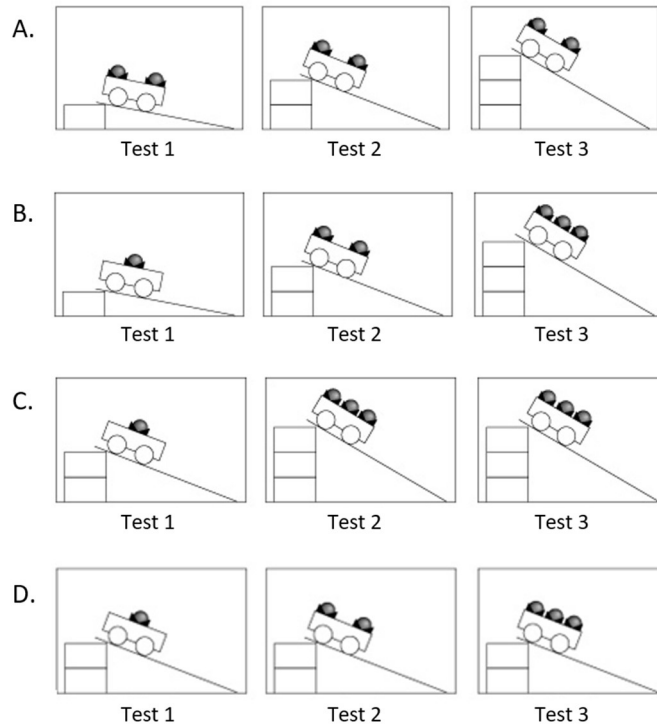


Figure 3. Example of a multiple choice question on NOS view.

Two students want to know who has the heavier kit. They weigh the two kits and disagree. How can they be sure of their conclusion?

- A. They ask the teacher.
- B. They ask other pupils to weigh the kits and take the opinion of the majority.
- C. They weigh the two kits again, changing hands.
- D. They use a balance.

Figure 4. Examples of questions on students' attitude towards science.

- I prefer to learn science by doing experiments [practical work in science];
- I like reading science magazines and books [science outside school];
- I do well in science [self-esteem in science];
- Later on, I intend to study science (physics, medicine, engineering, etc.) [future participation in science].

Figure 5. Frequency distributions of the scientific activities implemented by the 98 primary teachers in their classrooms.

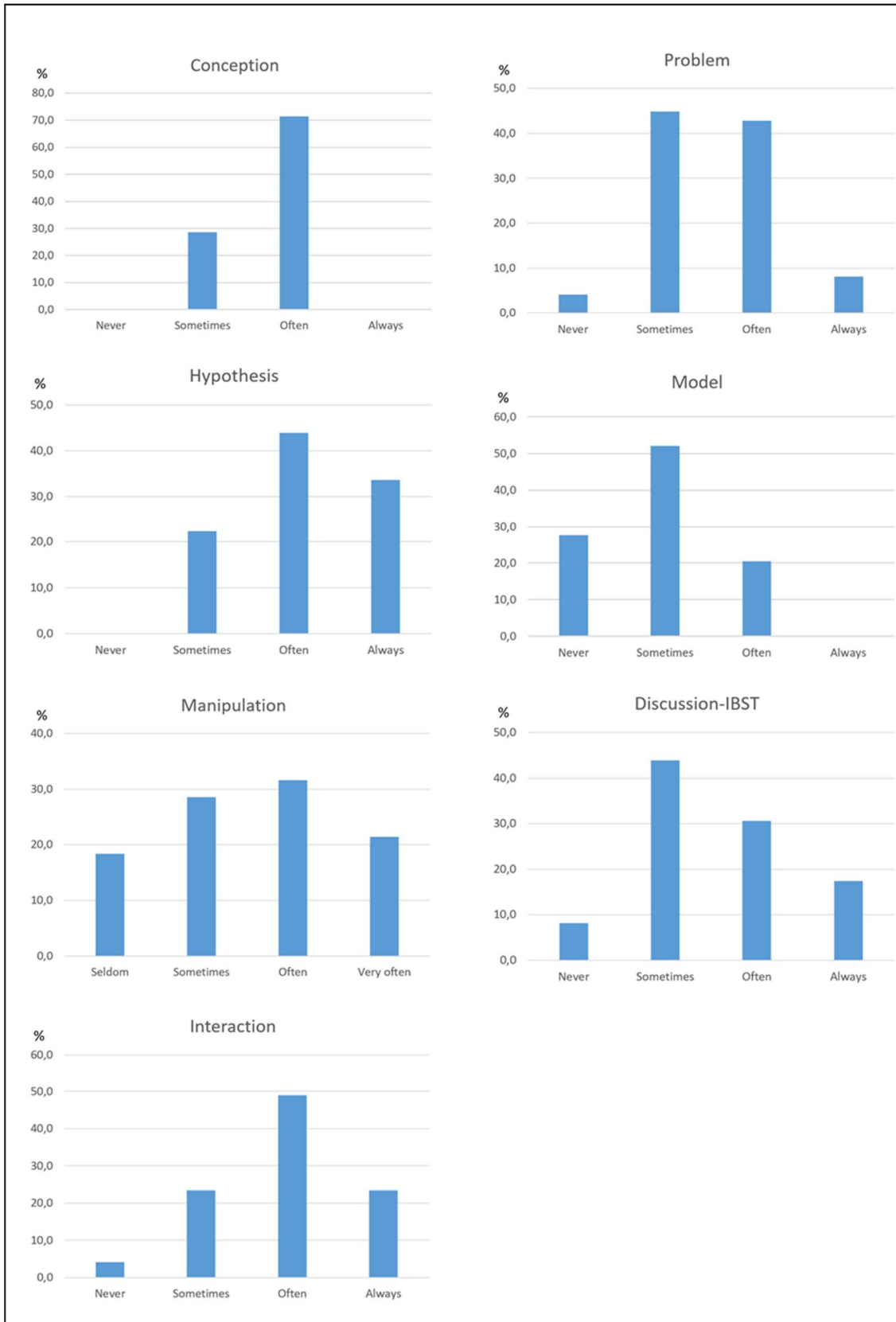


Figure 6. Clusters of science teaching practices derived from an MCA analysis. Four clusters are distinguished on this two-dimensional factorial map, each colour corresponding to a different cluster. The coloured dots represent the 98 teachers of the study.

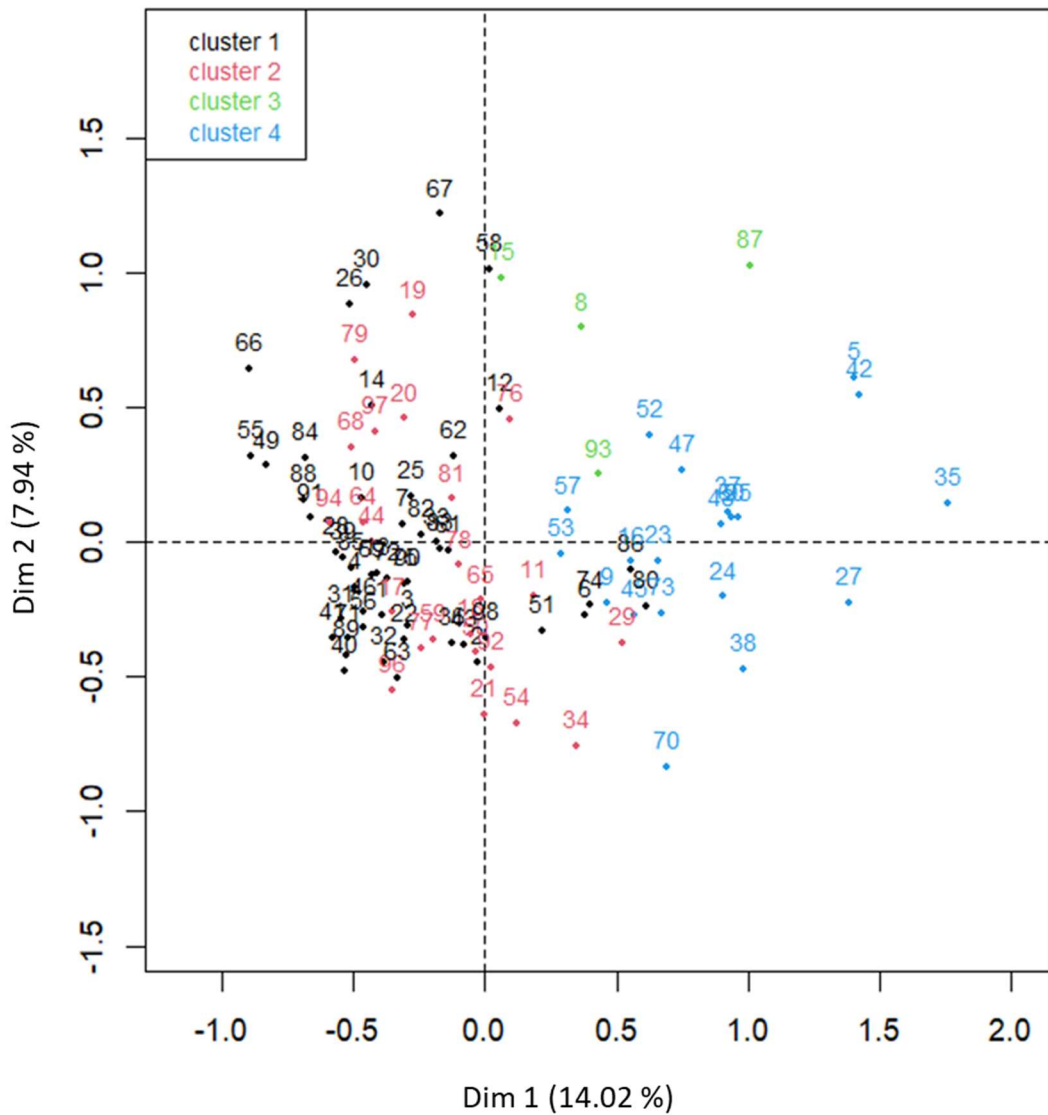


Figure 7. Correlations between the levels of student measures derived from an MCA analysis. Four measures are considered, each colour corresponding to a different student measure: scientific knowledge (here referred as Knowledge), inquiry skills (Skills), NOS views (NOS), and attitude towards science (Attitude). The different levels of students on these four measures, represented by discs, are the variables used to construct the axes of this two-dimensional factorial map. The distance between two discs represents the correlation between the corresponding variables (the smaller the distance, the higher the correlation). The size of the discs is related to the number of students.

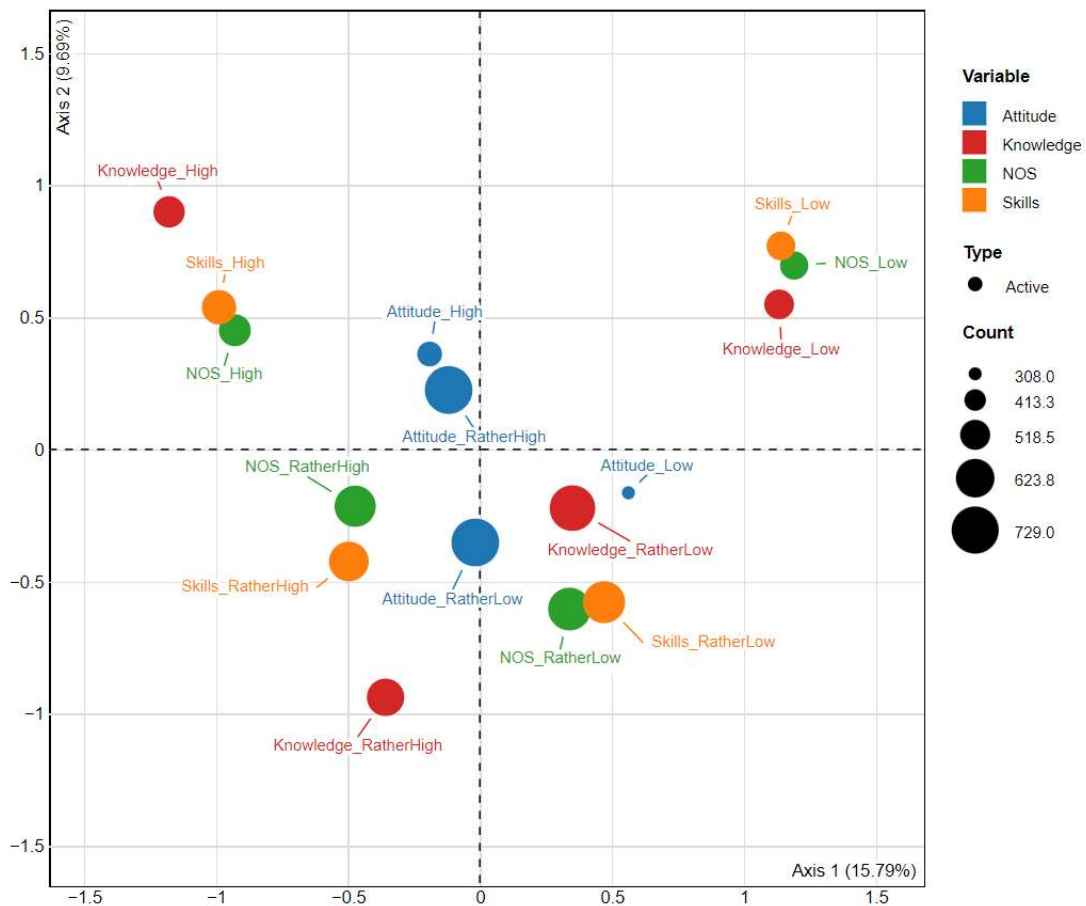


Figure 8. Correlations between the frequencies of the different science teaching practices and the levels of student measures derived from an MCA analysis. This graph is identical to the one in Figure 6, except that the frequencies of the different teaching practices have been added as supplementary variables (i.e. they do not contribute to the construction of the axes). Each red cross represents a given frequency of a certain teaching practice. To avoid making the graph unreadable, the labels associated to these crosses are not shown, except for the two crosses which are slightly off-centre. The graph shows that all the red crosses are concentrated in the middle of the factorial map, which means that the frequencies of the different teaching practices are very weakly correlated with the levels of the student measures.



Figure 9. Implication relations between the frequencies of the different science teaching practices and the levels of student measures derived from an ISA analysis. The arrows represent implications that are above a certain threshold value. Each arrow colour corresponds to a different threshold value: 75 (grey), 85 (green), 95 (blue), 99 (red).

