The Dutch chemistry curriculum for upper secondary schools has prescribed inquiry-based student learning since 1997. For some decades inquiry tasks have been a feature of school science in various countries (1). As in other countries, some of our chemistry teachers are used to recipe-geared practical work and face difficulties in teaching using an inquiry-based approach for student learning (2). These difficulties motivated five chemistry high school teachers from four schools in the area to seek help at our institutions. We agreed to start a collaboration with those teachers to also address the criticism that the version of scientific investigation taught in secondary school portrays a narrow and incomplete image of real science (3–6).

Together we decided to design and implement a curriculum unit creating a simulated inquiry community of upper-secondary chemistry students (ages 16–17) to enhance inquiry-based student learning. In this process we were interested in two questions. One relates to the design: “What characterizes a successful design process and product?” The other relates to implementing the design: “What changes in conceptual knowledge regarding domain-specific concepts occur when students do an inquiry-based activity in a simulated inquiry community?”

Designing Inquiry-Based Environments and Activities

Collaborating in the Process

First of all we established a network with the five chemistry teachers and the authors. The participants met every six weeks for about two hours. Forming this network involved teachers in the design process and all benefitted from their teaching experience (7–8).

From working together we expected an educational design that would be feasible in practice and would lead to an increase in student conceptual knowledge.

One of the authors observed the design process that originated in the meetings. These observations were documented immediately after the meetings and were sent via e-mail to all participants. They read and verified the observations. In the next meeting amendments were made and the observations were finalized. From these written documents we came to the following description of the design process.

In the first two meetings, the teachers and researchers became acquainted with each other by describing their experience. It turned out that all teachers had more than five years of experience in chemistry teaching at the upper-secondary level. However, they hardly had any experience with teaching inquiry-based learning. Their students were used to practical work that the teachers referred to as “cookbook” practices.

In the following six meetings we extensively discussed various inquiry-based learning models. We agreed to consider the student inquiry learning process as a cyclic and iterative one (9–11). Moreover, we have based that learning on the Procedural and Conceptual Knowledge in Science (PACKS) model (12). According to this model, conceptual knowledge means that students need to understand the nature of inquiry as well as relevant, domain-specific concepts and empirical evidence to adequately conduct inquiry. Procedural knowledge, on the other hand, relates to whether students can interpret the task, select correct equipment, and can draw and evaluate conclusions.

We have extended the PACKS model (see Figure 1) because we also consider students’ involvement as crucial in the learning process (13–15). Engaging students’ interest and participation
Research: Science and Education

Research: Science and Education can be enhanced by making the inquiry task—in the eyes of the students—interesting, important, and valuable to them (16).

In the ninth meeting we decided that the students of the four schools were going to form the inquiry community. We discussed how to create inquiry-based student learning and we decided that the students would be cast in a (simulated) role of “researchers” (17). As in a real research practice, they would work in teams in an inquiry community (18, 19) on the same inquiry problem, then write a first report, peer-assess another report, evaluate their peers’ comments, and write a final report. Furthermore, to encourage the involvement of the students, we decided that the first and final report would be published on a Web site and that the peer assessment would be held on an Internet symposium. Moreover, an independent jury would judge all final reports for an inquiry prize. The best inquiry report would be published in a Dutch journal for science and technology. To further value the students’ work, the final inquiry reports would be part of their school exam.

In another six network meetings we designed a three-month-long student inquiry project on Diffusion: Moving Particles with an inquiry problem on the relation between the solvated ion masses ($M^+ / M^-$) and the distance traveled in distilled water. This topic was chosen because salts, dissolving, and precipitation were topics that would soon come up in the students’ curriculum.

The Product

The designed material consists of a Web site with a student workbook with explanatory text and worksheets, a teacher guide, a cyber tracker, and an Internet symposium.

The workbook starts with the planning and the topic of the project and some general remarks on why chemists do research. Then, the students start with brainstorming about examples related to diffusion. They predict, observe, and explain (20) the movement of particles in the diffusion demonstration experiment on NH3 gas and HCl gas (see Figure 2). They further study the cyber tracker on the Web site. This tracker contains an applet on dissolving solid sodium chloride (21) and links to URLs concerning the diffusion of gases, solids, and liquids. The tracker serves as an introduction for students to relevant theory on diffusion.

We expect that these three activities will direct the students’ attention to conceptual knowledge on diffusion. In the PACKS model this conceptual knowledge falls under relevant, domain-specific topics (see Figure 1).

Then students conduct a guided experiment by dissolving a crystal of KI and a crystal of Pb(NO3)2 in distilled water at opposite sides of a Petri dish and observing the location of the resulting precipitate (see Figure 3). The hazardous character of lead(II) nitrate is indicated and students are instructed to dispose products in the proper waste drums.

This guided experiment prepares students to study and understand an exemplary research article on the diffusion of ions, A Liquid-Phase Diffusion Experiment (22). This part of the project is related to conceptual knowledge on the nature of the inquiry example (see Figure 1). With this knowledge they can assess the quality of the selection of combinations of ions and the number of combinations as made by its authors (see Figure 4). Moreover, conceptual knowledge on the nature of the inquiry example could help students decide on the selection and number of combinations in their own in-

Figure 2. The demonstration experiment on the movement of NH3 gas and HCl gas.

Figure 3. Guided experiment diagram showing a crystal of Pb(NO3)2 and a crystal of KI in distilled water. The gray line indicates the location of the resulting precipitate.

Figure 4. Plot of the inverse ratio of the solvated ion mass versus the ratio of the distances traveled; an $x = y$ line is superimposed. (Adapted from ref 22.)
Students investigate the validity of the conclusion, based on the results in Figure 4, of the authors (22) who state that: $d^+/d^- = (M^+ + 6\text{H}_2\text{O})/(M^- + 6\text{H}_2\text{O})$ with $d$ being the distance traveled and $M$ being the mass of the ion.

Implementing the Activities in the Classroom

Eighty students (ages 16–17) from five classes in four different schools joined the inquiry community. To determine change in concept knowledge regarding diffusion, we transcribed and analyzed (23) audio tapes of the discussion between three groups of students in each of the five classes ($N = 31$ students). We also analyzed individually filled-out student worksheets ($N = 80$), team inquiry plans, and final reports ($N = 32$), and the students’ definitions of the concepts diffusion, solubility, and precipitation ($N = 80$). Two of us independently analyzed and interpreted all the data. In the event of a different interpretation a discussion took place until consensus was reached.

Brainstorming

Analysis of the transcripts of the students’ brainstorming on diffusion revealed that all students initially related diffusion to gases—for example, the movement of oxygen in the lungs or perfume spreading in the air—but they did not come up with examples of diffusion linked to solids or liquids.

Demonstration Experiment

Coding the worksheets on the prediction, observation, and explanation in the diffusion demonstration of NH$_3$ gas plus HCl gas ($N = 78$) showed no great difference between the five classes. All students predicted that when simultaneously released on each end of the same glass tube, the gases would produce a white precipitate of solid NH$_4$Cl upon meeting each other. However, concerning the part of the tube where the white precipitate would form, the students thought differently, even after group discussion. After the experiment was demonstrated, though, 59% of the students had a correct explanation that the mass of the particle determines the velocity of the particle (see Table 1).

Guided Experiment

Analysis of the worksheets regarding the guided experiment combining KI(s) and Pb(NO$_3$)$_2$(s) indicated that all students correctly observed and wrote down that the yellow precipitate PbI$_2$(s) occurred at the side of the Petri dish where the Pb(NO$_3$)$_2$(s) was dissolved in the distilled water. Analysis of the transcripts, however, revealed that all students explained their observation in terms of formula masses of substances instead of solvated masses of ions (e.g., see the transcript inTextbox 1).

Inquiry Plans

The inquiry plans of the 32 teams showed that all students correctly considered the combinations of ions as selected by the authors of the example research (22) suitable for a precipitation reaction. All teams concluded that the four samples (see Figure 4) are not enough to reach the conclusion as stated by the authors in the research example.

Students in 28 of the teams planned to measure the distance traveled by two solvated ions from separate soluble salts, correctly indicating the precipitates that would be formed. The four remaining teams planned to measure the effect of the temperature on the velocity of a correctly selected, specific ion.

**Table 1. Comparison of Students’ Predictions and Explanations in the Demonstration of the Reaction of HCl(g) and NH$_3$(g)**

<table>
<thead>
<tr>
<th>Reaction Predictions and Explanations</th>
<th>Before Group Discussion ($N = 78$)</th>
<th>After Group Discussion ($N = 78$)</th>
<th>After Observation ($N = 78$); (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prediction of the Position of the White Precipitate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side of NH$_3$(g)</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Middle of the tube</td>
<td>51</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Side of HCl(g)</td>
<td>19</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>Explanation of the Observed Movement of the Gases</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass of the particle</td>
<td>3</td>
<td>9</td>
<td>46 (59)</td>
</tr>
<tr>
<td>Mass of the substance</td>
<td>7</td>
<td>7</td>
<td>13 (17)</td>
</tr>
<tr>
<td>Equal velocity</td>
<td>41</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td>Indifferent</td>
<td>27</td>
<td>23</td>
<td>19 (24)</td>
</tr>
</tbody>
</table>

Textbox 1. Transcript of part of an exchange between two students after they conducted the guided-inquiry experiment.
Final Reports

Most students (94%) wrote a first report and a final report, of which 51% of those students made correct adjustments in their final report. All adjustments can be related to the peer review in the Internet symposium. The final reports revealed that, in their conclusion section, 94% of the teams ($N = 32$) correctly refer to masses of ions in relation to the salts (substances) of which they are solutes. Moreover, these teams correctly refer to the velocity of an ion in distilled water in terms of the mass of an ion and the number of water molecules attached to the ion (see Textbox 2).

Definitions of Concepts

The concepts of diffusion and solubility were correctly defined by 82 and 80%, respectively, of the students ($N = 78$) in terms of substances, ions, and hydrated ions. Precipitation was correctly defined by 85% of the students as a solid formed (for an example see Textbox 3).

Discussion and Conclusions

For experienced chemistry teachers, the conceptual knowledge part—on the nature of the inquiry and the relevant, domain-specific concepts—in the PACKS model (see Figure 1) was quite suitable means to guide the process of designing a student inquiry project in the Diffusion: Moving Particles unit. It is important to take ample time even for enthusiastic and very motivated chemistry teachers to discuss the model. In our case, this familiarization took about six network meetings, and even during the process of designing the project materials, the model, and how to interpret it, was very often part of our discussions.

Our expectation about the velocity of ions seems to be right. The velocity depends on the mass of the ion and the number of hydrated water molecules. Only the combination of the copper ion (from the copper nitrate salt) and the hydroxide ion (from the substance sodium hydroxide) was an exception. In this case, the heavier copper ion moved faster than the less heavy hydroxide ion.

Textbox 2. Extract from the conclusion in the final report by Lars and Peter.

<table>
<thead>
<tr>
<th>Diffusion:</th>
</tr>
</thead>
<tbody>
<tr>
<td>First I thought that it was about gases, but now I understand that gas, liquid, and solid particles can diffuse, and that ions, because of a negative or positive charge, are surrounded by water molecules. I also learned that the velocity of a particle or ion depends on the mass of the ion not forgetting the water molecules.</td>
</tr>
<tr>
<td>Solubility:</td>
</tr>
<tr>
<td>In water salts can fall apart into ions, so that they become hydrated.</td>
</tr>
<tr>
<td>Precipitation:</td>
</tr>
<tr>
<td>A process in which two ions form a solid substance in water, like the yellow stuff.</td>
</tr>
</tbody>
</table>

Textbox 3. Examples of one student’s definitions regarding the concepts of diffusion, solubility, and precipitation.

With the discussion above in mind, we conclude that in the guided experiment in which they relate velocity to formula masses of substances instead of to masses of hydrated ions (see Textbox 1), their thinking and thinking concerns the question of whether the yellow precipitate will appear in the middle of the Petri dish, and which of the substances, lead(II) nitrate or potassium iodide, is heavier. They seem to completely ignore ion dissociation.

However, from the judgment of students concerning the combinations of ions used in the research example (22), we conclude that the students have a correct understanding of solubility of salts and the possibility of precipitation reactions, but on a macroscopic level. This understanding changes again to the microscopic level when the students write their own inquiry plans. Here, all students write about which ions they expect to react in a precipitation process. From what they write in their final reports, we conclude that student understanding remains focused on the microscopic level, because almost all students wrote about the velocity of the ion in terms of the mass of the ion and the hydrated water molecules (see Textbox 1).

With the discussion above in mind, we conclude that in this inquiry project student learning occurred regarding diffusion, dissolution, and precipitation. Our hypothesis is that this learning occurs because of the successive student inquiry actions that give students the opportunity to have a repetitive cognitive handling of the relevant chemical concepts. Moreover, this was made possible by participating in an inquiry community that can be characterized by activities that resemble real research activities (25).
Literature Cited


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