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Article

Children learn that material hardness is linked to atoms and bonds by playing a game: a case study

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Abstract

Recent findings show that primary school children can understand aspects of the particulate nature of matter after following formal teaching interventions. We investigated whether primary school children who have not had formal lessons about atoms, can explain the hardness of materials using concepts of atoms and bonds after playing a specifically designed, cooperative resource management game. In pre-, post-, and two retention interviews, we examined the understanding of 12 children who played the game. We also investigated the children's interest/enjoyment and effort expectancy about the game. Half of the children justified material hardness by atoms and bonds throughout all interview phases, three missed out on one of the post-interviews, and the remaining three responded otherwise or had other prior knowledge about atoms before playing. Additionally, the usability of the game was assessed by 7 primary school teachers. The participating teachers were not formally trained in chemistry but could play the game and confirmed their willingness to use it to teach material properties in primary school. These findings support that games can ignite the formation of abstract but fundamental science concepts in children's thinking. The authors suggest that atoms can be introduced into primary school by using games.

1. Introduction

The particulate nature of matter is one of the most troublesome concepts for chemistry students, i.e., atoms and molecules, and their relationship to the material world as we perceive it [1]–[3]. Students harbor various misconceptions about the submicroscopic scale, e.g., matter is continuous [4]–[8], atoms of copper are malleable like the copper itself [9], hard like the stone, light like the air, or frozen like the ice itself [10], or molecules expand when a substance is heated [11]. Students also struggle with understanding the different types and strengths of chemical bonds [12]. Misconceptions about such concepts are resistant to change [13], and therefore, it may be argued that atoms and molecules are too difficult for primary students, and that such teaching should be postponed to secondary school [14], [15]. However, recent studies have shown that young children can be successfully taught particle concepts using tangible and interactive models [16], [17], or dialectic interviews [18].

1.1 Atoms and particles are made accessible to children

Teaching particle concepts to young children is no impossible task anymore [17]–[20]. In contrast, teaching abstract concepts such as atoms could take place in primary school so that children's understanding of matter and the world forms before children come up with own, false beliefs [13], [15]. However, Samarapungavan et al. [16], [21] pinpoint one of the key challenges for such teaching: primary teachers have practical difficulties in conducting such lesson sequences since they are not typically trained in chemistry and may feel uncomfortable in incorporating atom concepts in their classes. Therefore, other ways of teaching may become of interest.

A game-based approach that does not require explicit teaching has potential. Holbert and Wilensky [22] describe a game-based intervention that relates macroscopic hardness with particle interaction. In their 2D side scrolling game, players finish levels by overcoming obstacles and gaps and by manipulating blocks in their internal atomic structure. Thereby, the blocks may be very stable or bouncy, depending on how the particles interact, and players explore how the interconnections between particles result in different properties for the block. The authors describe their game as an object-to-think with, designed after the "CAR" principle (constructible authentic representations) [ibid.]. Holbert and Wilensky [22] report that after students played the game, they made considerable gains in explaining material properties with particle structure. Moreover, there was no extensive training for students necessary before they could play the game.

This approach suggests that even small-scale interventions like playing a game can lead to significant changes in children's understanding of matter. However, teachers remain the most important element when deciding for or against an activity before it can be used. Therefore, some good practices leading to the use of games in school should be highlighted, with a case study presented in this paper.

1.2 Games in the classroom

When investigating the general acceptance of (video) games in the classroom, Bourgonjon et al. [23] found that teachers must find it useful and believe that a game should provide opportunities for learning before they intend to use it in class. In a later study, perceived usefulness as well as a positive attitude towards games influenced the intention to use an educational game [24]. It is reported that pre-service teachers would adopt existing games designed for educational purposes rather than entertainment games or game creation activities [25], or commercially available games [26], because they do not have the time, resources or expertise to design games themselves [25], [26]. However, explaining the games seemed to be an issue for teachers [27]. Croft, in an interview with Thrower, illustrates the point [28]. She argues that teachers must elaborate on the key ideas of games and point out their relevance to real life. Moreover, teachers' views on and evaluation of new teaching aids are essential for the success of educational games (ibid.). Therefore, it is important to investigate whether teachers find games useful and simple enough for their classroom.

1.3 The game and the purpose of the study

This study explores whether a custom-made board game about atoms helps primary school students understand the idea that solids are made up of atoms, and material hardness emerges from the strength of bonds between atoms. The game is called *Roaring Robots* (previously Material Monsters), and it was tested in Flanders and Australia [29]. From a cognitive perspective, the approach of the game directs children to think of matter as being particulate

Figure 1. Main board of the game (center), atom cards, dice and score board (top), and two exemplary challenges (right). The picture is taken from Dumin et al. [29].

[15], [30]. The game itself is a cooperative resource management game for 2 to 4 players. Intrinsic integration was its main design guideline [31], [32].

In principle, players have three movements per turn. They gather resources, i.e., different atoms and bonds, and together they decide which atoms and bonds are suitable for challenges in which robots need to withstand various hardness related events (Figure 1). For example, a falling anvil requires a robot to be very hard/stable (Figure 1 bottom right), but to stop a crate the robot needs to be less hard (Figure 1 center right). For both challenges, different combinations of atoms and bonds can be chosen. There are three different types of atoms (red, green, blue) with different slots for bonds (thick or thin). The atoms and bonds determine the dice which can be used to resolve a challenge. The dice have different values (red is high, green is medium, blue is low for atoms; thick is high and thin is low for bonds). For the flipped robot (Figure 1, center right), players could use the dice for green atoms and thick bonds because the robot is equipped with two tiles of both green atoms and thick bonds. The different atom and bond tiles are shown in Figure 2. More details on the rules of the game can be found in Dumin et al. [29].

Our objective for this study is to highlight potential learning outcomes for students, the motivational appeal of the game, the potential effort which players (including the teachers) need to invest, and the game's usefulness. Therefore, we attempt to answer these research questions:

RQ1: Can a short intervention with a specifically designed board game influence late primary school children's ideas of material hardness, and if so, what are the changes in their ideas?

RQ2: Is the game a motivating and fun experience for children and teachers and is it sufficiently easy to play (i.e., do they have to put a lot of effort in it)?

RQ3: Do primary school teachers find the game a valuable teaching tool?

Figure 2. The different atoms and bonds in the game (left results in dice for red atoms and thick bonds; right results in dice for blue atoms and thin bonds) [29].

2. Methods and Material

We constructed an interview protocol consisting of pre-, post-, and retention interviews within a convergent parallel, mixed method design [33]. The qualitative data comprise the participants' response patterns during the interview stages (Section 2.2). The quantitative data are responses to a questionnaire in pre- and post- interviews (Section 2.3). The convergent parallel design was used to get insights into children's thinking from different perspectives.

The pre-interview assessed whether participants have any relevant prior knowledge about atoms and bonds. For that, it is necessary to explore their knowledge of materials and material hardness (which is likely very basic). Then, one can evaluate whether there is a connection between prior knowledge of atoms and material hardness.

The questionnaires assessed interest/enjoyment (i.e., intrinsic motivation) and effort expectancy of children and primary school teachers [34], [35], and value/usefulness for teachers [36].

It was assumed that most participants have heard of atoms. We did not expect any sophisticated responses even though aspects of the nature of matter (e.g., that substances exist in different states of aggregation) are part of the year 5 curriculum in Australia [37]. In the chemical sciences strand of year 6, students investigate reversible or irreversible changes to materials. In both years, the achievement standards highlight that substance classifications and changes of materials are investigated by observation (i.e., see, touch, smell, etc.) [37]. However, it was assumed that particles at the submicroscopic scale may have been introduced at Year 5 but year 6 students' prior knowledge was expected to be higher than year 5 students' knowledge.

The study received ethical approval by the ethics committee of KU Leuven, the leading university in this study, under the application G-2021-4605-R6(AMD).

2.1 Participants and practicalities

The target groups were children aged 10 to 12 from years 5 and 6 of primary school, as well as primary school teachers (pre-, and in-service). In total, 12 children (10 girls and 2 boys, all English speaking) and 7 teachers (6 female, 1 male; 4 English, 3 Dutch speaking) participated in the study. Parents and teachers signed informed consents before participating. The interviews and game sessions for both groups took place in separate classrooms of the respective schools or wherever else convenient for the teachers. Pre- and post-interviews were conducted directly before and after playing, where possible. Participants watched a video (about 7 min) in their native language that explained the game before playing (Figure 3). The interviews were audio recorded.

2.2 Open-ended interview questions (qualitative)

The interviews were semi-structured and consisted of open-ended questions directly before and after playing the game for both groups. The children also completed two retention interviews. The course of the interview for children and teachers is depicted in Figure 3.

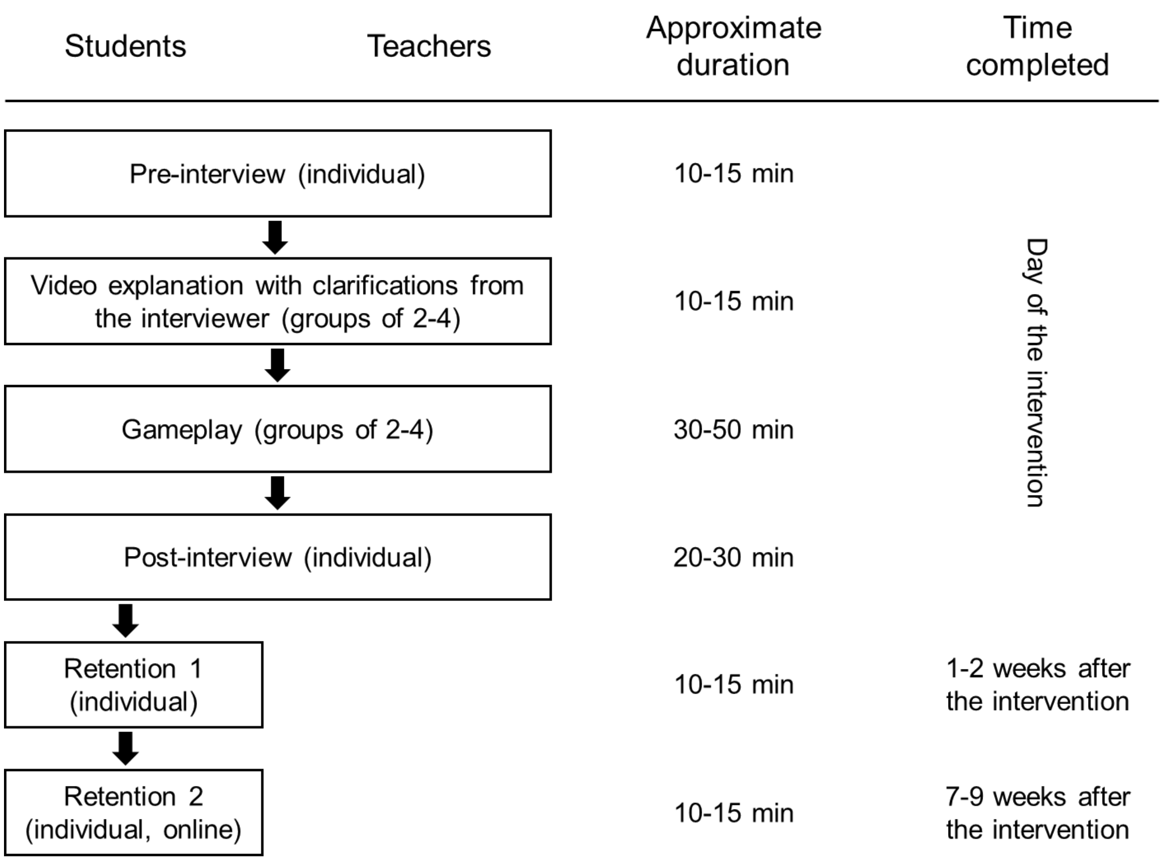


Figure 3. The different stages of the interview with approximate durations and times of completion.

The questions concerning prior knowledge were based on Samarapungavan et al. [16] and Haeusler and Donovan [17] and were adjusted for the game where necessary. Interaction between the participants was encouraged. To identify children's ideas about the relative hardness of materials, they were shown four different materials, a bar of steel, a bar of PTFE (plastic), a block of wood, and a foam (Figure S1 in the supplementary material). The children were asked to describe them, order them from hard to soft, and explain their order, or why they think one material is harder than another material (Table S1 to S5 in the supplementary material).

2.3 Questionnaire and scales (quantitative)

Participants' interest and enjoyment (IE), effort expectancy (EE), and teachers' opinion on the game's value and usability (VU) were measured with validated scales [34]–[36], [38]. IE measures the intrinsic motivation inherent to any kind of activity [34], EE is the degree of ease associated with a system or technology [35], and VU shows how useful participants find an activity [36]. (Perceived) usefulness, a comparable scale to VU, was reported as an important predictor for behavioral intention for (serious) games [24], [39].

Besides the instruments described so far, we identified if the participants had experience in playing games, and if they had a preference for games. Experience affects the use of games and how games are perceived as learning opportunities by students [40]. Preference was defined as "positive feelings about games for learning and predicted choice for video games in the classroom" [40, p. 1147]. The subscales Experience with games and Preference for games were used to measure these factors [23], [40].

The participants completed scales for Experience and Preference at the end of the pre-interview. The scales for IE, EE, and VU (only teachers), were filled after watching the explanatory video, and at the end of the post-interview. All items were given a 5-point Likert scale, and the scales were filled with pen and paper by the participants (Table S6 to S10).

For a physical activity like a board game, some adjustments to the items were necessary. For example, "activity" or "video game" were replaced with "game". Any reversed items were written in the positive sense for children (not teachers) because some children found them confusing during preliminary tests (e.g., IE3 "I thought this was an interesting activity" instead of "I thought this was a boring activity"). We also placed smileys to indicate the levels of agreement for children [41] (the final questionnaire for both groups can be found in the supplementary material).

2.4 Data collection and analysis

Data collection was carried out between October 2022 and February 2023. All interviews with the 12 children and 7 teachers were transcribed and coded by the first author via inductive, in-vivo coding [42]. Codes were grouped into categories according to the responses from participants (some categories/response patterns were not mutually exclusive). The third author coded responses from one child and one teacher with a coding manual. After an initial comparison, 85 % agreement was observed. After that, ambiguous categories where the raters disagreed were combined. All other disagreements were resolved upon discussion.

Non-parametric tests were chosen for the questionnaire analysis due to the small sample size. Spearman's rho was used to find correlations, Wilcoxon Signed Rank Tests showed differences between pre- and post-tests, and a Mann-Whitney *U* Test highlighted potential differences between the groups [43].

3. Results

We present our results as follows: we begin with an assessment of the participants' prior knowledge about atoms. This is important to establish a base reference to the learning outcome after playing the game (Section 3.1). After that, we assess the impact of the game directly after playing (post) and longer after playing (retention) (Section 3.2). The explanation of material hardness was the main learning goal and therefore we base the impact of the game on that assessment (Section 3.3). It is unavoidable that participants, especially the children, make additional assumptions about atoms that are tacit in the game and that may go beyond its learning goal. Therefore, we provide additional data on such assumptions in Section 3.4.

Next to the learning goal of the game, it is important that players find it interesting (IE), easy to learn (EE), and in the case of teachers, a valuable teaching aid (VU). These issues were addressed in the questionnaire that participants filled during the pre- and post- interviews and the data is presented in Section 3.5 (IE and EE) and Section 3.6 (VU).

3.1 Participants' prior knowledge (pre)

Participants' prior knowledge can be summarized as (1) prior knowledge of atoms, and (2) explanations of material hardness.

(1) Prior knowledge about atoms. All participants have at least heard the term atom after being prompted, and they knew that atoms were very small. For example:

> Interviewer: Okay, so you've already heard of the word atom before. Can you explain what atoms are and what they do?
> Child 11: Uh, atoms, they are like little, little particles or something that create like the universe, like … . Trying to get an example in my head. Uh, they're like little … they're particles, but um … they can't be seen by any eye of like animals or anything, they just exist. I don't know how we, how mankind found it. It's just, uh, it's just a little particle that creates everything.

> Interviewer Okay, we're almost done. Have you heard of the word atom before?
> Child 4: Yeah.
> Interviewer What are atoms, what do they do? Can you explain that to me?
> Child 4: Uhm, they're made up, so it's everything, like in materials, like basically everything around in the world is made up of atoms.

(2) Explanations of material hardness. Most participants chose the expected order (steel, plastic, wood, foam) with a few exceptions. When justifying their choices, all children referred to higher stability of the steel, or that the harder materials are used to hold other objects (e.g., a bridge or house). So, they described macroscopic properties. None of the children explained hardness with submicroscopic concepts. Three teachers either referred to atom packing or chemicals.

> Interviewer: Okay, if we think that metal is hard and the foam soft, do we know why that is? [Pause] So that's difficult, right?
> Child 2: Cause metal is used in lots of places. So in … you can feel it a lot. And how they break.

> Interviewer: And why is that, why is that order?
> Child 4: I just feel like, uhm obviously foam is really squishy, and wood, can like come apart easily so if you'd touched it things can break off. Plastic is like really hard, but I guess it can chip away and metal is just really strong.

> Interviewer: And why would you order them in this way?
> Child 6: Cause I can identify that some are harder and some are softer. Some are stronger, some are weaker.
> Interviewer: Okay. So, just by the looks or the feel.
> Child 6: Maybe the weight too.

Interviewer: Yeah, that's a bit difficult. Why would you order them in this way?
Child 7: Because foam is usually softest. It compresses more when you touch it. Wood kind of moves when you touch it. It's like compressible. Plastic is a bit less, depending on the plastic. And metal just isn't really like squishy.
Interviewer: And do we know why metal is not squishy and the others are?
Child 7: It comes from the underground and it's compressed there, I think. It's not organic.

Participants were divided into prior knowledge groups as shown in Table 1. Based on the observed response patterns, these distinctions seemed reasonable. Despite the limited number of participants, two exceptions still need to be mentioned. One child already drew what resembled an atom nucleus with orbits for electrons, and a teacher already justified hardness by different bonding behavior of particles. These two were considered as exceptionally high prior knowledge but are still grouped in the higher prior knowledge category.

Table 1. Groups of prior knowledge about atoms.

Groups	Children in this group …	Teachers in this group …
Higher prior knowledge	mentioned atoms or molecules by themselves, for example that materials are made of atoms, and they also envisioned particles or alike when drawing how the materials look through a very strong microscope (5 children).	described different particle behavior in different states (6 teachers).
Expected prior knowledge	did not mention atoms, particles, or molecules by themselves. However, when being prompted, they were familiar with the term atom and knew that they are "in stuff" (5 children).	drew particles, but did not mention other aspects indicating more advanced knowledge (1 teacher).
Lower prior knowledge	did not mention atoms, particles, or molecules by themselves during the interview. After being prompted, they were not sure what atoms are or what they do (2 children).	

3.2 Impact of the game (post and retention)

The main learning outcome of the game is how participants justify material hardness, directly and longer after playing the game.

Explanations of material hardness. Chemistry encompasses three interconnected domains: the macroscopic, the submicroscopic, and the symbolic domain [1]. Students often do not grasp how the microscopic domain determines macroscopic phenomena [1], [3], [6]. Essentially, material properties depend on (*i*) the atomic composition of a material (which elements are contained in the material), and (*ii*) the type of chemical bonds between them (how atoms and molecules are interacting with each other). Stating that steel is hard because it is (made of) steel, or that a rubber band is elastic because it is (made of) rubber is false reasoning, similarly to other misconceptions mentioned earlier [4]–[12]. However, such explanations seem rather intuitive for young children, or even untrained adults.

Participants' explanations of material hardness can be seen in Figure 4 and Figure 5. Although individuals may have mentioned both macroscopic and microscopic concepts, a shift towards microscopic aspects is observable. Before playing the game, children did not explain material hardness with atoms and/or bonds. After playing the game, they did so until two months later. Some mentioned bonds explicitly. Others described that atoms decide how strong materials are. Most prominently, no participant judged by his or her intuition anymore. For a few participants, the game triggered some prior knowledge. For example, they mentioned that hardness comes from particles, a term not mentioned in the game, and instead of referencing

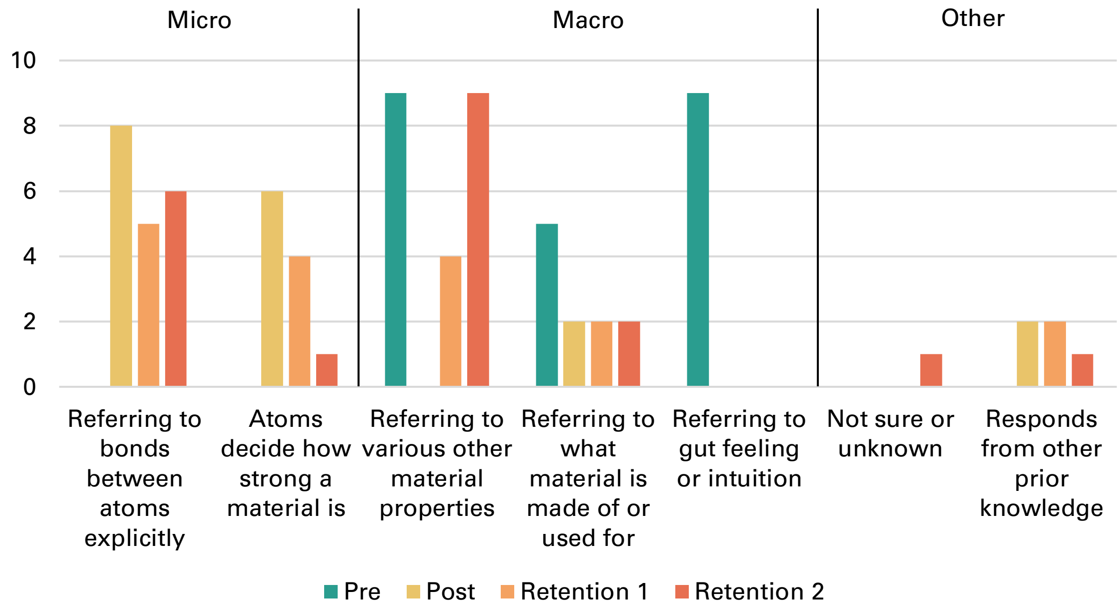


Figure 4. Children's explanations of material hardness during the different interview stages.

bonds, they recalled how atoms are packed. Teachers understood the central learning goal of the game well since all refer to atoms and bonds instead of macroscopic properties. Some participants mentioned thick/strong and weak/thin bonds interchangeably, others only used thick/thin or strong/weak. It can be assumed that thicker bonds were thought as stronger and thinner bonds as weaker, but participants' explicit ideas of bonds were not further investigated. Table 2 shows excerpts from the interviews. Table 3 shows in detail how each child refers to micro- or macroscopic notions in the different interview stages.

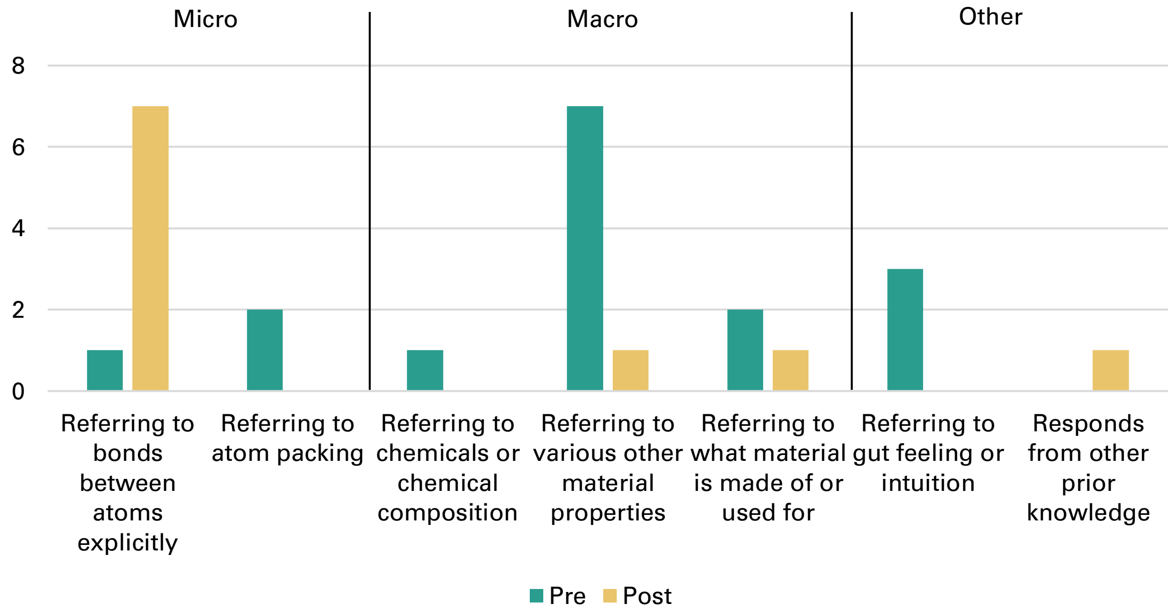


Figure 5. Teachers' explanations of material hardness during the different interview stages.

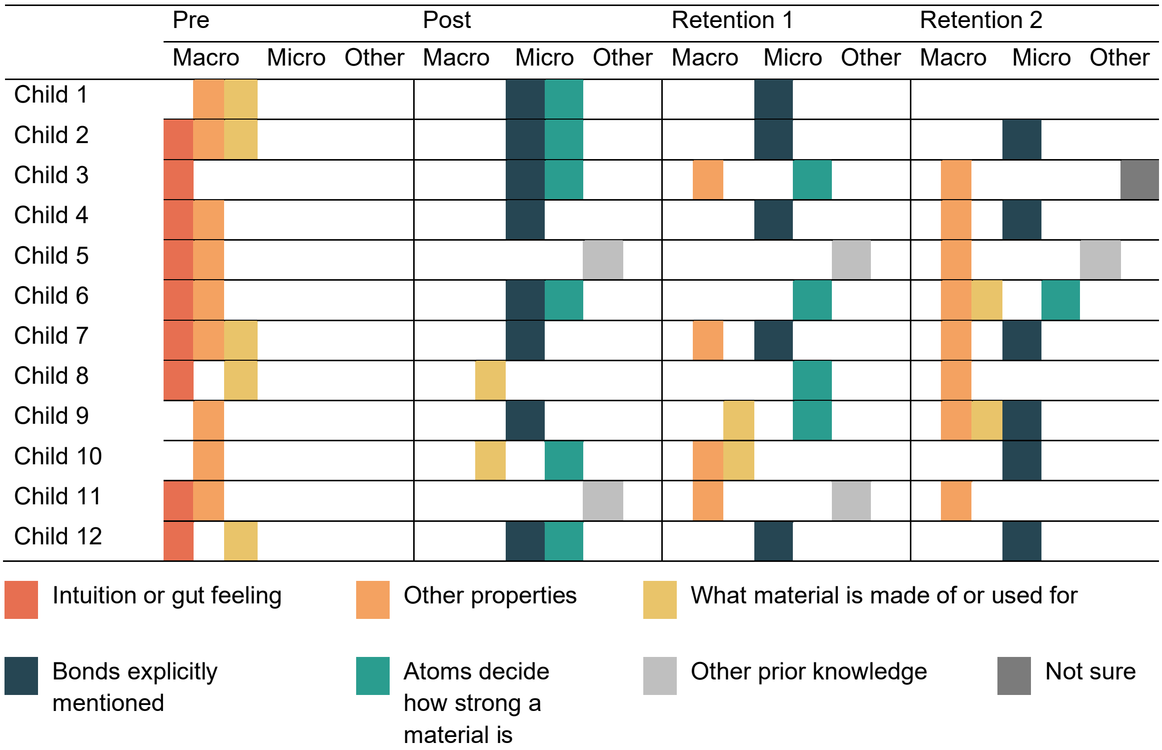
Table 2. Excerpts from different interview stages after playing the game.

Stage	Response patterns	Interview excerpts
Post	Bonds explicitly mentioned Atoms decide how strong a material is	Interviewer: Okay. So, the first question I have for you would be: why do you think are some materials harder than others? Child 2: Because of the atoms they're made of, the atoms could be built differently. Interviewer: It's okay, it's not so easy to answer, but if you think what kind of feature or property they have, how do they relate to hardness of materials? Child 2: The stronger they put together, like … Interviewer: The stronger they bond? [The child was very shy and needed a hint] Child 2: Yeah.
	Bonds explicitly mentioned	Interviewer: All right. Why do you think are some materials harder than others? Child 4: Because they have stronger atom bonds. Interviewer: Okay. They have stronger atom bonds, what do you mean? Child 4: So like the bonds are thicker I guess.
	Bonds explicitly mentioned Atoms decide how strong a material is	Interviewer: Do you remember the game we played yesterday? Good. I hoped so. My first question for you would be: why do you think are some materials harder than others? What do you say? Child 6: Um, it depends on what makes them. Interviewer: Okay. And, what do you mean with what makes them? Child 6: Well, the, the different atoms that combined to make something stronger or weaker. [The interview was interrupted] Interviewer: Good, we can sit again. So, how would you say do the atoms relate to the materials in real life? Child 6: So, like what the atoms do? Well, the atoms either make an object stronger or a different texture, like soft or hard, they can be used for different purposes. They don't, they're not all exactly the same.
	Bonds explicitly mentioned	Interviewer: Okay. Do you remember the game we played yesterday? My first question would be: why would you say are some materials harder than others? Child 7: Because the atoms and bonds are harder inside than other materials Interviewer: Okay. So you say they're harder in the one material, and well, not so hard in the other material? Child 7: Yeah.
Retention 1	Bonds explicitly mentioned	Interviewer: So, there was steel, there was plastic, there was wood, and the foam. But why would you think is the steel harder than the foam or the wood? Child 4: Um, the, um, probably because the atoms that make, makes it up is like tougher and have stronger bonds.
	Other macroscopic properties Bonds explicitly mentioned	Interviewer: We also talked about materials and you ordered them from hard to soft, like plastic, wood, and the foam. Why do you think are some materials harder than others? Child 7: Harder atoms and bonds? Interviewer: Okay. But they differ in the atoms as well. Child 7: Yeah. The atoms are also different between … Interviewer: And only the atoms or also something else? Child 7: Um, bonds. So if it's hollow … I forgot what else I was going to say.
Retention 2	Other macroscopic properties What materials are made of Atoms decide how strong a material is	Interviewer: Okay. But why are some materials harder than others, per se? Child 6: Cause it's different atoms that are used to make it. Chemicals. Interviewer: Okay. Only the atoms different? Child 6: Um, no, the um. The types of chemicals and stuff they use to make it like that.

3.3 Assessment of the impact of the game

In association to hardness justification, three groups could be distinguished for the children. One group continuously related material hardness to atoms or bonds in the post-, and both retention interviews (6 children). The second group considered atoms or bonds in at least two out of three interviews (3 children), and the third group did so in one of the interviews, or they continued to respond from other prior knowledge which they did not utter before playing the game (3 children). The last child with exceptionally high prior knowledge continued to answer what he/she already knew beforehand. It can be mentioned that two children of the third group considered atoms or bonds only during the first retention interview (and not in the post-interview). The inferred groups, including the number of children, are given in Figure 6. All teachers understood the takeaway from the game (and they were only interviewed once).

Table 3. Response patterns per child in pre-, post-, and both retention interviews.



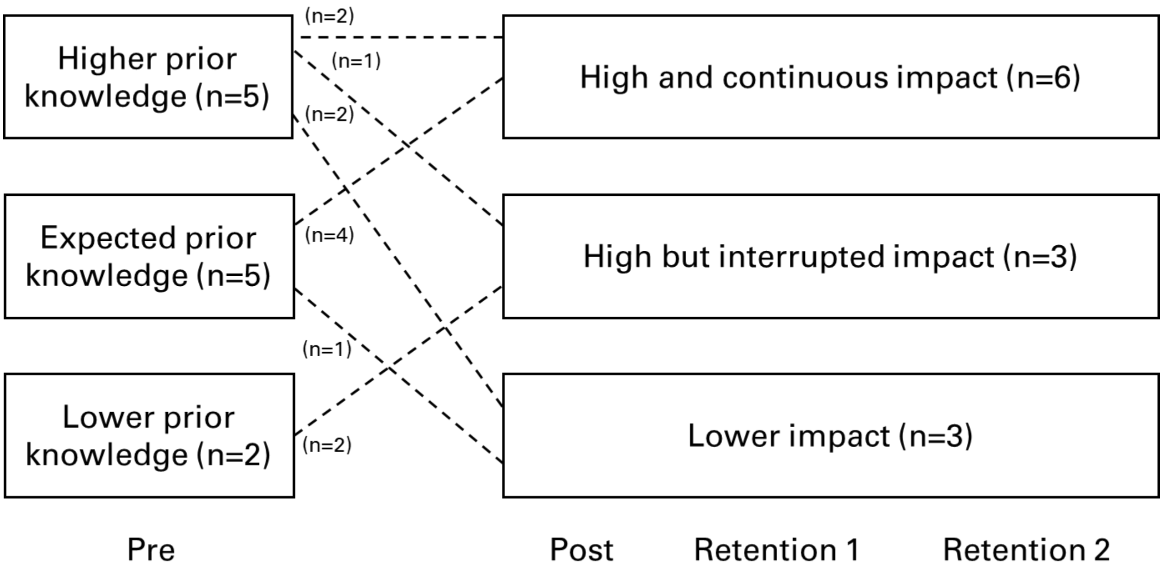


Figure 6. Qualitative impact on children's ideas about atoms over time.

3.4 Additional assumptions of children on atoms

The game does not teach the size of atoms, or whether atoms can be seen through a microscope. However, we assessed whether children make assumptions about atoms or bonds that are not explicitly in the game during both retention interviews. Table 4 shows results from a multiple-choice task and Table 5 shows results from a gap text (only 11 children completed the second retention interview and 9 filled all the questions). In the former, children decided whether various statements about atoms are true or not, and in the latter, the children filled similar statements with given terms (see Figure S2 and S3 in the supplementary material).

Table 4. Statements on atoms that children may consider to be true.

	Statement [a]	Retention 1	Retention 2 [b]
1	Atoms are very small. With a microscope, you can see them.	9	7
2	Atoms are very small. Even with a microscope, you cannot see them.	3	2
3	Materials are made of atoms.	11	9
4	Atoms are in materials to support them	3	4
5	Some materials are harder than others because the atoms have stronger bonds	12	9
6	Some materials are harder than others because they are used for more challenging things	5	2
7	There is only one type of atom for all materials	0	0
8	Atoms can be mixed in materials	12	9
9	Different materials can have different atoms	9	9
10	Some atoms are stronger than other atoms	9	5
11	There are no stronger atoms. Atoms only differ in how they can make bonds with each other	3	4
12	The strength of a material is because atoms work together	10	5
13	You can distinguish atoms by their colors	4	3

[a] Only the underlined statements can be considered correct in the chemical sense
[b] 9 out of 12 children handed in full data sets

Before and after playing the game, participants were asked to draw 4 different materials that were shown to them (steel, solid PTFE plastic, wood, and a foam) when looking through a (very strong) microscope (Figure 7). It was ensured not to preempt the term "atom" and use the term uttered by the participants (see Table S1 and S2 in the supplementary material). Different types of transitions could be observed. Before playing, some participants drew some kind of particles closely or loosely packed, others drew lines and shapes resembling the structure of the specific material. After playing, some participants drew atoms like those represented in the game, others retained their previous imaginations. Other participants thought that atomic composition of the materials looks exactly like that shown in the game, but some participants already knew that atoms cannot be seen by a microscope, and therefore they could not possibly see structures like those represented in the game. Moreover, the game does not teach the atomic composition of materials, nor are such materials mentioned in it. Therefore, we did not include the drawings in the impact assessment.

3.5 Interest/enjoyment (IE) and effort expectancy (EE)

For the children, the correlations between pre- and post-IE as well as EE were significant and highly positive. Considering IE, children's motivation before playing was already high and it increased after playing. A Wilcoxon Signed Rank Test indicated a statistically significant difference in IE between pre- and post-test (M_{pre} = 25.17, SD = 2.62; M_{post} = 26.92, SD = 2.94; Z = 2.33, p < .020). Towards EE, children did not expect the game to be very difficult, and their confidence to play it increased significantly after playing (M_{pre} = 15.25, SD = 2.60; M_{post} = 16.83, SD = 2.25; Z = 2.54, p < .011). So, the game seemed to be a quite enjoyable experience for the children although they were already motivated before playing, and they were very confident to play it (again). Additionally, the questionnaire indicated that the group of children in this study was familiar but not very experienced with games in general (M = 14.42; SD = 2.54). However, they showed a high preference to use games in the classroom (M = 12.33; SD = 2.15). The latter could be expected, but we assumed they were more familiar with games. Finally, children's experience with and preference towards games was not correlated to their motivation (IE) or confidence to play it (EE). All descriptive statistics and a correlation matrix for children are shown in Table 6.

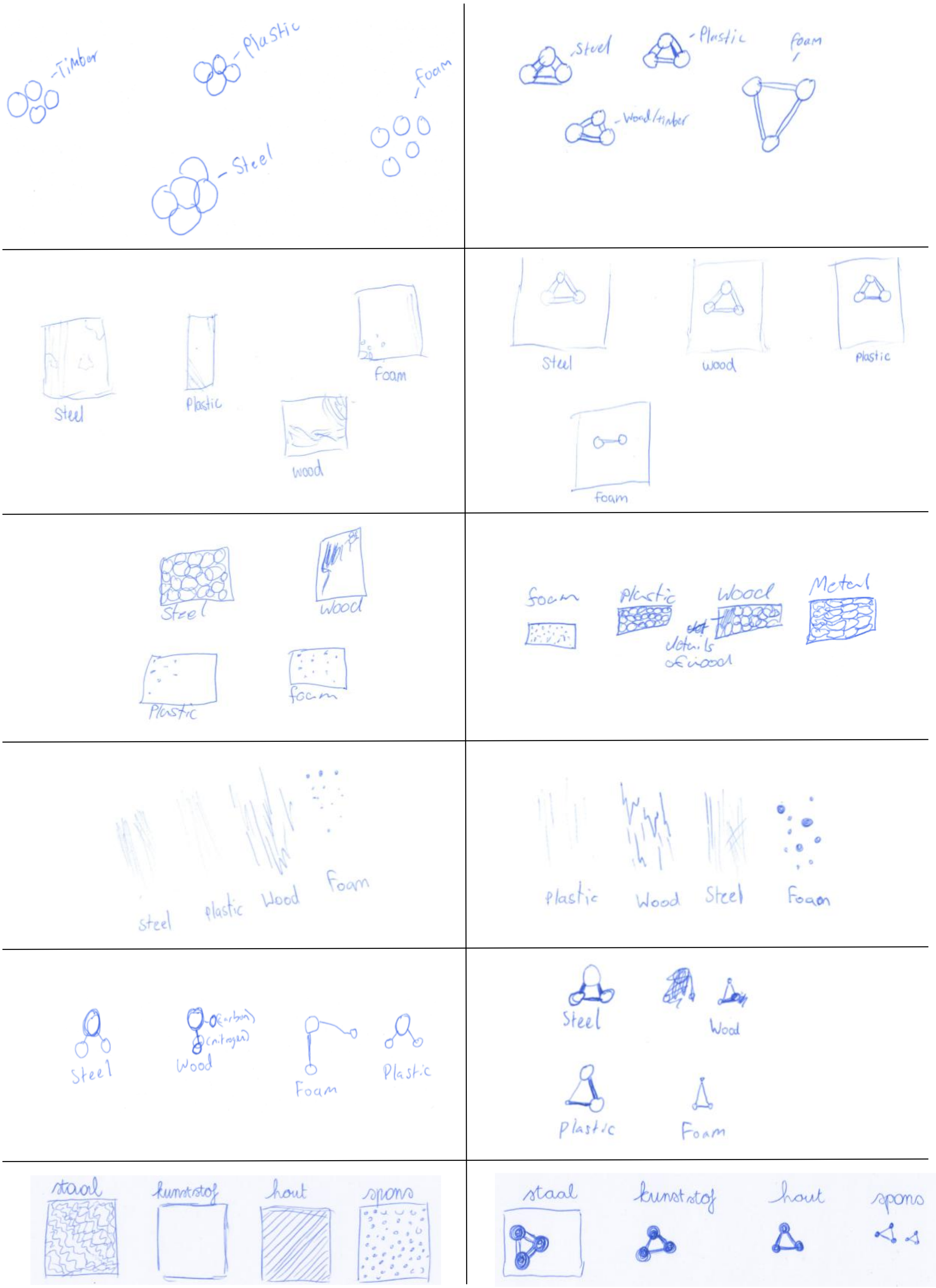


Figure 7. Examples for pre- (left) and post-drawings (right); the first 4 examples are from children, the last 2 from teachers (Dutch/English: staal/steel, kunststof/plastic, hout/wood, spons/foam or sponge).

Table 5. A gap text with different terms related to atoms and bonds.

	Gap text [a]	Retention 1	Retention 2 [b]
1	Everything we can see and touch is made of _____	atoms (12)	atoms (7), particles (2)
2	One ___ see them	cannot (7), microscope (3), can (1), missing (1)	cannot (9)
3	and they _____ have colors	don't (6), do (4), can (2)	don't (5), do (4)
4	____ also make up	atoms (10), particles (1), stuff (1)	atoms (8), bonds (1)
5	____ for example steel	materials (10), stuff (2), things (1)	materials (9)
6	Steel is ____ because	strong (11), hard (1)	strong (9)
7	it is made of ____	atoms (10), thick atoms (1), strong atoms (1)	atoms (7), strong atoms (1), bonds (1)
8	and the ____ between them are very strong	bonds (12)	bonds (9)
9	Wood is not so ____	strong (10), hard (2)	strong (9)
10	because the ____ are not so strong	bonds (7), atoms (5)	bonds (6), atoms (3)
11	Steel and wood are different because their ____	atoms (11), bonds (1)	atoms (5), particles (1), quarks (1)
12	have different capacities to make ____	bonds (2), materials (8), strong (1), stuff (1)	bonds (3), atoms (2) materials (1), energy (1), things (1)
13	But they only work _____	together (9), collectively (3)	together (5), collectively (4)

[a] Only the underlined terms were considered correct if a child used them in the corresponding gaps
[b] 9 children handed in full data sets

For teachers, no correlations were found between pre- and post-IE (M_{pre} = 24.29, *SD* = 2.69; M_{post} = 25.71, *SD* = 4.79) and pre- and post-EE (M_{pre} = 11.29, *SD* = 2.29; M_{post} = 14.86, *SD* = 2.27), which were both expected. A Wilcoxon Signed Rank Test did not indicate any statistically significant difference between pre- and post-IE (Z = .84, p < .400), however, for EE it was significant ($Z = 2.21, p < .027$). That indicated that teachers find the game enjoyable, but not significantly more than before playing, but they were significantly more confident to play it again once they knew how it worked. The survey further suggested that teachers were only mildly experienced with games (*M* = 11.71; *SD* = 1.38) but they would consider using games in the classroom (*M* = 12.86; *SD* = 1.57). A significant and highly positive correlation between post-EE and experience as well as post-IE was found. So, if the teacher found the game easy to understand, he or she would have more experience in playing games and perceive more enjoyment in this game. Especially for adult players, such correlations seem coherent. Adults or teachers might be more hesitant towards games per se, and they might not play many games in their everyday life. Descriptive statistics and the correlation matrix for experience, preference, IE, and EE of teachers are shown in Table 7.

Table 6. Descriptive analysis and Spearman correlation matrix of all constructs for children.

Scales	n	M	SD	Experience	Preference	Pre-IE	Post-IE	Pre-EE
Experience	12	14.42	2.54					
Preference	12	12.33	2.15	.25				
Pre-IE	12	25.17	2.62	.12	.28			
Post-IE	12	26.92	2.94	.02	.11	.59*		
Pre-EE	12	15.25	2.60	.38	.03	-.30	-.09	
Post-EE	12	16.83	2.25	.20	.06	-.29	-.15	.70*

**p* < .05 level (two-tailed); M: mean; SD: standard deviation

Table 7. Descriptive analysis and Spearman correlation matrix for experience, preference, IE, and EE of teachers.

Scales	n	M	SD	Experience	Preference	Pre-IE	Post-IE	Pre-EE
Experience	7	11.71	1.38					
Preference	7	12.86	1.57	.19				
Pre-IE	7	24.29	2.69	.19	.52			
Post-IE	7	25.71	4.79	.62	.70	.15		
Pre-EE	7	11.29	2.29	.36	-.15	.38	-.32	
Post-EE	7	14.86	2.27	.80*	.32	-.16	.82*	-.05

**p* < .05 level (two-tailed); M: mean; SD: standard deviation

Lastly, it was interesting to compare the two groups. A Mann-Whitney *U* test indicated significant differences between children and teachers for pre-EE (U = 12.0, p = .010) and experience (U = 12.5, p = .010). That suggests that children were a lot more confident to play the game (children: M_{Rank} = 12.5; teachers: M_{Rank} = 5.71) and they were also more experienced with games per se (children: M_{Rank} = 12.46; teachers: M_{Rank} = 5.79). There were no significant differences found between pre- and post- changes for IE (children: M_{Rank} = 10.13; teachers: M_{Rank} = 9.79) and EE (children: M_{Rank} = 8.59; teachers: M_{Rank} = 12.75) between the groups.

3.6 Value, usefulness (VU)

The questionnaire revealed that pre- and post-VU were highly positively correlated at a significant level. Further, post-VU and post-IE seemed to be correlated very highly and significantly. So, if the game was found more interesting, it was also found more useful. A Wilcoxon Signed Rank Test did not indicate any statistically significant difference in pre- and post-VU (Z = 1.265, p < .206). The post-mean was very high, but teachers already assumed the game to be valuable during the pre-interview (M_{pre} = 30.14, SD = 3.85; M_{post} = 31.57, *SD* = 3.69). Detailed descriptive statistics and Spearman correlations for VU and the other constructs are shown in Table 8.

Table 8. Descriptive analysis and Spearman correlation matrix for VU of teachers.

Scales	n	M	SD	Experience	Preference	Pre-IE	Post-IE	Pre-EE	Post-EE	Pre-VU
Pre-VU	7	30.14	3.85	.54	.41	.49	.71	-.28	.43	
Post-VU	7	31.57	3.69	.59	.67	.40	.93**	-.19	.69	.82*

**p* < .05 level (two-tailed); ***p* < .01 level (two-tailed); M: mean; SD: standard deviation

4. Discussion

4.1 Qualitative impact of the game on students' conception of atoms, bonding and hardness

This section discusses RQ1 (can a short intervention with a specifically designed board game influence late primary school children's ideas of material hardness, and if so, what are the changes in their ideas?).

During the pre-interviews, children mainly describe the "look and feel" of the material and they conflate the terms hardness, strength, or solidity [44]. For example, some of our children explained that hard(er) materials are (more) solid. This is consistent with the claims of Skamp [45] who states that children confuse these concepts or use such terms interchangeably. Most children claim that atoms make up materials and a few did so when prompted. Because our data was not rich enough, we were unable to categorize children's responses into more fine grained models (such as Renström et al. [8]). Some children drew atoms in different sizes or distances for the different materials. No child claimed that atoms bond to other atoms and that bonding strength determined different hardness of materials. We are not aware that atoms have been investigated in association with material hardness in comparable studies. Although Haeusler and Donovan [17, pp. 37–41] specifically ask to draw atoms (not how materials look through a microscope), some children drew circles and spheres before the intervention (if they had prior knowledge of atoms), and some of their students had prior knowledge about atoms or molecules. During their teaching sequence aided by digital tools, Samarapungavan et al. [16] reported that also kindergarteners believe that materials are composed of small, but visible or touchable pieces or invisible tiny particles. Although our group was older than those in the mentioned studies, our pre-intervention findings seem to be comparable and coherent. Comparing findings between genders was not possible in this study, since there were only 2 boys and 10 girls (and 1 male, and 6 female teachers).

After the intervention, children explained the different hardness of materials quite frequently in terms of atoms and/or bonds and continued to do so until two months after playing the game. Interestingly, some children's explanations became more detailed from one interview to the next. This may be due to a practice effect (due to repeated interviews), or alternatively, as a consequence of children discussing their ideas with their peers or parents between the interviews. Additionally, TV or media may have influenced children's ideas about science [46], [47].

Moreover, it was quite prominent that children answer from their intuition before but not after playing (Figure 4). Although they often refer to other properties of the materials [21], our group did not explain material hardness with other material properties directly after the intervention. However, they do so again in the retention interviews. They seem to infer that such an explanation is misguided, but their conclusion was only temporary. A similar picture emerges for the teachers, who rarely mention atoms and bonds beforehand but often mention them after the intervention. In addition, the teachers described other properties of materials only before but not after playing.

Holbert and Wilensky [22] report similar findings in their study about a digital educational game on atoms. Their participants mention (atomic) structure and bond(s) when they think about real materials a week after playing their game. Therefore, Holbert and Wilensky [22] argue that games should be designed as objects-to-think with. If a game is an entity beyond an imaginary circle with set rules (games may indeed be summarized like that), it can be assumed that this frequently encountered obstacle of educational games might be overcome. Both their game and ours followed similar design principles. Holbert and Wilensky [22] followed the constructible authentic representations (CAR) approach [48], whereas we followed the intrinsic integration design principle [29], [31]. However, both games share an important commonality, namely that there is room for exploration in how the atoms bind together. There is no clear solution to every obstacle/challenge in both games (maybe except for "maxing out" on bonds) but players frequently find satisfactory solutions to progress further. Moreover, our retention data shows that children remember the basic rules of the game and they continuously apply them in more realistic scenarios even after two months (Table 2 and Table 3). But most importantly, they continue to associate atoms/bonds to material hardness, even though this varies for individuals. Therefore, we deem our game to be an accessible and useful tool that influences players' thinking beyond the game's borders.

Previous research has shown that it is counterintuitive for children to represent non-granular objects as particulate on the submicroscopic scale [7], [19]. We could not confirm this difficulty in our study. Some children, who did not draw particles before playing the game, indeed progressed from drawing macroscopic lines and shapes for steel, plastic, wood, or foam towards drawing atomic structures like the fixed templates of the game (see Figure 7).

Our participants find it intuitive to think of materials being made of atoms, similar to the game, and they are able to create structures with atoms which relatively display the hardness of the materials. This further supports our claim that after playing the game, they think of hardness, as a concept emerging from atom bonding mechanisms rather than being inherent to a material. When reflecting on atom structures in real life, there was no sign that they think atoms look like the templates from the game. Given that our game is compact and no additional training is needed for teachers, finding about the emergence of hardness from atoms and bonds seems to be a rather valuable learning outcome which settles in between more sophisticated atom teaching interventions [16], [17], [19], [21].

We also need to re-consider design and terminology used in the game. The atoms were designed to prevent thinking they look like smaller parts of the material [29]. Also, atoms are neither strong nor weak (although we called them according to their color). To minimize the misconception that chemical bonds are submicroscopic objects with materiality, it would be better to speak of strong and weak bonds rather than thick or thin bonds. Although the participants did not seem to consider bonds to have materiality that change in design may prevent such misconceptions in the first place. In any case, such design and terminology should be addressed in science lessons where the game is used, or at least clarified in the rulebook. We do not see any sign that particles should rather be framed as molecules than atoms [18]. Both terms atoms and molecules seem to make clear that they are smaller than dust particles. Based on these findings, we deem RQ1 answered in the positive.

4.2 Participants views on enjoyment, ease of playing, and usefulness of the game

This section discusses RQ2 (is the game a motivating and fun experience for children and teachers and is it sufficiently easy to play, i.e., do they have to put a lot of effort in it) and RQ3 (do primary school teachers find the game a valuable teaching tool?).

Both open-ended questions and results from the IE survey suggested that most participants find the game an enjoyable experience and easy to play, at the latest after a few rounds. In other studies, intrinsic motivation has been found to be a predictor or moderator of learning during games. For example, Ninaus et al. [49] found that intrinsic motivation was most predictive for learning success in their game about rational numbers. However, they distinguished between the general interest in math and math self-efficacy, with self-efficacy being a stronger predictor than general interest. Interestingly, when general math interest was lower, they observed higher learning outcomes. Similar findings were confirmed in a later study [50], or observed for school contexts [51]. We could not apply any structural equation modelling to find predicting or influencing relationships between intrinsic motivation and the other scales. We also did not include self-efficacy since the scale seemed incompatible with our game. In our study, students and teachers reported high means of pre- and post-IE (which measures intrinsic motivation) with no significant differences between teachers and children. We found a highly significant correlation between post-IE and post-VU in teachers. So, the more interesting, the more useful they found the game. This observation seems reasonable, but we did not find any comparable studies which measure both constructs. In general, the authors are not aware of game-based learning interventions that combine scales of different questionnaires as done here.

The significant difference of pre-EE between children and teachers is unsurprising (so after explaining the game, but before playing it, children were confident to play it but teachers were not). The same accounts for the difference in experience (children were more experienced with games than teachers). This is because children probably play more games in comparison to teachers. In the study of Bourgonjon et al. [23], teachers were less experienced with games than in this study. We attribute the different experience levels between the studies to the time when each study was performed and the fact that we used an analog game. Therefore, higher experience of teachers with board games can be expected. However, it was reported elsewhere that teachers' experience with games was a minor influence before a game may be used [24].

What was more prominent for teachers was their hesitancy before playing, whilst afterwards they felt more confident to play and explain it. This is in line with other research which highlighted prior instruction before considering (digital) games in school [26], or that teachers think games take a lot of time to learn [25], [27]. Otherwise, our game seems to fit into the findings of Huizenga et al. [52] who find that games are, from teachers' perspective, motivating and supportive to learn a variety of subjects. Regarding science related topics they report "teachers mention that by using games, students start to realize how things work and that games offer them the opportunity to discover these processes themselves" [52, p. 112]; in our case, that is the concept of material hardness. Based on these findings, we deem RQ2 and RQ3 answered in the positive.

4.3 Considerations to complement science lessons

It is suggested that games should not replace traditional teaching but complement it [28]. Therefore, *Roaring Robots* could serve as a teaching aid for science lessons about atoms and, so far, these findings support this claim. A teacher could explain its rules in front of the class, then students could play in groups of 4 and the teacher acts as a guide during the session. Then, a discussion round could clarify or solidify the students' conclusions. However, some aspects need to be clarified so that children do not infer false conclusions that go beyond the game's learning goal (Section 3.4).

Before playing, children were already familiar with the fact that atoms constitute matter and that they were small. However, the game may seem to suggest that atoms can be seen through a microscope, and that atoms may have colors (Table 4, statement 1 and 2, and Table 5, gap 2 and 3). Although single atoms could be manipulated by scanning tunneling microscopes [53], it should still be assumed that atoms cannot be seen, even with a strong microscope, and that they do not have colors. However, ball and stick models for atoms are typically colored and why colors occur requires highly advanced knowledge to be fully understood. Therefore, the misconception about colors might be neglected at this stage.

Another outstanding misconception was that hardness of materials results from atoms being stronger/harder than others, rather than the capacity of atoms to make different bonds (Table 4, statement 10 and 11; Table 5, gap 11 and 12). Although red atoms from the game could make (more) stronger bonds than the others, it seems likely that children would acquire this misconception (red atoms came with a bigger dice and greater numbers). It needs to be repeated in a lesson that different atoms have different capacities to bond with other atoms and that atoms do not inherent any properties from the materials they constitute, a typically difficult concept [3].

Otherwise, even after two months, the data supports that a considerable number of children stick to the conclusions that atoms can be mixed in materials, a specific material can have several types of atoms, and its hardness comes from the bonds between its atoms which act as a collective (Table 4, statements 7-9 and 12, Table 5, gaps 6-10 and 13). As mentioned before, it seems that children view the hardness of materials as its strength (Table 5, gap 6 and 9). Although such paraphrasing of concepts is common, it might be worthwhile to put hardness before strength. If a teacher underlines important facts and clarifies the mentioned misconceptions, one can be confident that children take home such fundamental and important messages.

4.4 Limitations of this study

We are aware of the limitations of this work, in particular, the small number of participants. Initially, we aimed for a congruent parallel study design. This study was conducted during and near the end of the covid pandemic and we found that schools were unwilling to get involved in extracurricular projects. Therefore, the generalizability of our findings is limited.

Considering the qualitative data, when explaining material hardness, thematic saturation in the response patterns was reached after analyzing 6 of the 12 interviews (all stages). This is in line with previous research [54]. Guest et al. [55] argue that 11 to 12 interviews are enough even for high saturation of responses. In addition, the teachers' responses of our study were categorized into the same patterns as the children's responses. Therefore, one could argue that we did not miss relevant information in the qualitative data set. However, there is not yet sufficient evidence that a majority of young children successfully learn about atoms and bonds after playing this game. Considering the quantitative data, the generalizability of the IE, EE and VU questionnaires is limited due to the small sample size. For more generalizable conclusions, the game needs to be played by more children and teachers, and the questionnaire data needs to be analyzed with parametric counterparts of the statistical analysis used here. Also, it needs to mentioned that the scales were written in the positive to avoid confusion for the children.

Another limitation is that we based our questions on and compared our findings to studies about digital games. There are distinctive differences between digital and analog games with the latter often being more compact or cost-effective [56]. Compared to the vast body of literature on digital game based learning (GBL), analog GBL is very scarce [57], [58]. Although it seems clear that analog games also possess benefits for learning, they are not explicitly included in most studies or models. We find that models, assumptions, and attempts to predict and improve digital games for learning should also apply to analog games. However, there is no clear evidence for that. Despite trends of digitalization, we call for higher integration of analog games when investigating potential learning gains, motivational aspects, and usefulness of games in the classroom.

Lastly, teachers' prior chemistry knowledge may pose a considerable issue before the game may be used in class. Since chemistry is typically not a subject in primary or lower secondary schools, teachers for those grades often lack chemical expertise and they may be uncomfortable to use the game. Students may ask questions about atoms and bonds that go beyond the scope of the game. Although all teachers of our study understood the game and its learning goal, some were a bit hesitant to play it because they were unfamiliar with games or chemistry. A manual with more background information on atomic composition and molecular interactions in materials could help teachers to guide students beyond what was taught in the game. However, until atoms and molecules become part of the primary curriculum, only teachers who have had formal training or professional development in basic chemistry would be likely to use the game in their classrooms.

5. Conclusions

We have presented a case study which tested a custom-made board game about material hardness that emerges from the atoms and bonds involved. It was tested to determine knowledge gains, its enjoyability, and its potential value for supporting science lessons in primary school. We found that the game successfully introduced the fundamental concept that hardness of materials emerges because of the bonding between their atoms, and that the hardness of different materials is related to the strength of bonding between their atoms. Teachers consider this type of game useful in their classroom. Given that it is a physical board game, it constitutes a rather unique approach. It cannot replace traditional lessons on atoms. However, we see the board game as a contribution to a spiral curriculum about the atomic nature of matter. Our game can be seen as a tool with a very low threshold for usage since it requires no additional training other than understanding its rules. Thus, we deem it a valuable additive towards this research field. We highlighted the contributions of Holbert and Wilensky [22], and our works [29] because we contend that both games could be considered within other, more sophisticated interventions [16], [17], [19], [21]. We believe our results support the contention that game-inspired approaches find more common ground and complement science education in future.

Further research in the use of games to teach microscopic concepts would make a valuable contribution to the field of game-based learning in science. For this game, it would be worthwhile to investigate whether players think of a bond as something with materiality (like atoms that have mass) or as a force without materiality or substance. In future, one might use a modified version of the game as part of a professional development workshop for teachers centering around material properties and how atoms relate to them.

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Conflicts of interest

The authors have no conflict of interest to declare.

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