Learning and Instruction 16 (2006) 363–373

Learning and Instruction

www.elsevier.com/locate/learninstruc

The utility of implicit learning in the teaching of rules

Bjørn Sætrevik [a,*], Rolf Reber [b], Petter Sannum [b]

[a] *Department of Biological and Medical Psychology, University of Bergen, Jonas Lies vei 91, N-5009 Bergen, Norway*

[b] *Department of Psychosocial Science, University of Bergen, Christiesgate 12, N-5015 Bergen, Norway*

Abstract

The potential impact of implicit learning on education has been repeatedly stressed, though little research has examined this connection directly. The current paper describes two experiments that, inspired by artificial grammar learning experiments, examine the utility of implicit learning as a method for teaching atomic bonding rules to 11–12 year old school children. Two groups were given tasks that led to explicit rule learning; two other groups were given tasks that did not lead to rule learning; and a control group was trained on irrelevant stimuli. We observed an implicit learning effect, but learning was much more effective when more explicit ways of teaching were employed. These findings suggest that mere exposure to regular material is not sufficient for effective learning of rules, and that an explicit approach to instruction is advisable.

Keywords: Chemistry teaching; Implicit learning; Rule abstraction; Science teaching

1. Introduction

Some of our personal knowledge about the world is in the form of rules. Acquiring the rules that structure the environment is part of formal education, such as the rules of grammar for first and second language, the operational rules of calculus and fractions, the laws of optics, the underlying regularities within ecosystems, the algorithms of weather forecasting, the rules of Mendelian genetics, and the atomic bonding rules in chemistry. The question arises whether such rule knowledge can be learnt implicitly.

The term implicit learning, first coined by Reber (1967), describes a situation where a person acquires knowledge of covariations in the environment without explicit intention of learning, without awareness of the learning process and without knowledge of what has been learned. In the artificial grammar learning experiment, participants are instructed to memorize stimuli structured by a rule. In a later test phase, they are able to classify stimuli into regular and irregular items with above-chance accuracy without being able to verbalize the rule.

A debate raged over the question whether rules can be abstracted implicitly, as Reber (1989) claimed to have shown in experiments on artificial grammar learning. However, other findings suggest that the participants in such experiments do not learn an abstracted rule, but extract some probabilistic information about the composition of sequences (Shanks & St. John, 1994). In experiments that demonstrated transfer from one stimuli domain to another – a finding

* Corresponding author. Tel.: +47 55 58 31 81; fax: +47 55 58 98 79.
E-mail address: bjorn.satrevik@psybp.uib.no (B. Sætrevik).

0959-4752/$ - see front matter
doi:10.1016/j.learninstruc.2006.07.006

that apparently supports the notion of rule abstraction – a transfer decrement effect was observed: transfer performance was always lower than performance on stimulus materials with the same surface structure (Dienes & Altman, 1997). Other experiments showed that if information about repetition of elements was removed, the transfer effect in implicit learning disappeared (Tunney & Altmann, 1999). For example, a novel test item (such as ZZLJH) could be recognized as having the same grammar as an item remembered from training (such as VVPTN), because the participant notes that both strings start with a doubled letter. If this is the case, transfer effects do not rely on abstraction, but on some other underlying mechanism. Recent evidence suggests that experts in atonal music are able to abstract rules that cannot be explained with the acquisition of sequential dependencies (Dienes & Lounguet-Higgins, 2004).

Different alternative mechanisms have been proposed as involved in the implicit learning of regularities; (a) people extract similarities between training and test materials (Pothos & Bailey, 2002; Vokey & Brooks, 1992); (b) people retrieve fragmentary knowledge about training materials (Perruchet & Pacteau, 1990); (c) people experience higher processing fluency when a stimulus is regular rather than irregular and rely on this processing experience as information for the classification task (Whittlesea & Dorken, 1993). Although more evidence has been accumulated in support of the latter positions than in support of implicit rule abstraction, the issue has not yet been settled: it is possible that training in laboratory experiments is too short and the materials are too artificial to find implicit rule abstraction. Moreover, the theoretical debate may have prevented research on implicit learning in everyday settings. Regardless of the underlying computational mechanisms, implicit learning could be a powerful tool for teaching at school and in everyday life.

In an influential book, Reber (1993) claimed that powerful mechanisms of implicit learning remain untapped because current educational practice overemphasizes conscious learning at the expense of implicit processes. Although he acknowledges that some guidance is necessary for maximal learning, he stated that "the studies on implicit learning suggest that school curricula should be modified to include more exposure to the variations that the specific subject matter displays and less time and energy should be spent on specific tutoring of rules and formulas. [...] this explicit element has little or no educational effect without the extended immersion in the stimulus display. We do not learn about the underlying structure of complex environments by explicit instruction; we must experience the patterns of covariation for ourselves" (p. 159). According to this position, students could profit from experiencing material first hand without prior knowledge, with minimal guidance and without an explicit focus on extracting structure. Learning would be a direct effect of experience, and instructions and directions could in some cases even have a detrimental effect on learning (see Reber, 1993). Other authors agreed with the idea that the impact of implicit learning in education and instruction is immense (Berry & Broadbent, 1984; Reber, 1993; Robinson, 1997). Despite its potential importance, implicit learning has only to a limited extent been tested in natural settings (Pacton, Perruchet, Fayol, & Cleeremans, 2001; Robinson, 1997), and instruction in educational settings remains to a large extent based on explicit teaching.

1.1. Implicit learning in everyday settings

Pacton et al. (2001) and Robinson (1997) were among the few who have examined implicit learning in everyday settings. Both studies intended to address the issue of implicit rule abstraction versus retrieval of fragmentary knowledge.

Pacton et al. (2001) addressed the argument that experiments in implicit learning often do not give enough training to implicitly abstract the rule, and that this is why learning in laboratory experiments shows distribution learning rather than rule abstraction. They decided to study real-life learning of orthographic regularities over several years. In a series of experiments, they tested French first, second and third graders for their sensitivity for whether and when written letters can be doubled in nonwords. Children as young as first grade were sensitive to which consonants were more frequently used as double consonants, and which were seldom or never used as double consonants. This sensitivity increased with grade level, although the children had not been taught the rules. They were also sensitive to which positions double consonants could appear in and to the fact that vowels can never be doubled in their language. These results indicate the existence of implicit learning. In order to see whether the performance relied on remembered instances or abstracted rules, the children were shown nonwords. Certain letters that cannot legally be doubled in French language had been doubled in legal and illegal positions of those nonwords. The participants had to classify these nonwords in order to see if their rules of orthographic regularities could be transferred to novel stimuli. The knowledge of legal positions of double letters extended to the tasks where illegal letters were doubled, but performance on such tasks were lower, which parallels the above-mentioned transfer decrement effect. If knowledge of orthographic regularities was completely abstract, performance on classifying the position of illegally doubled letters in nonwords would have been as high as performance on legally doubled letters in nonwords. Pacton et al. (2001) therefore concluded that real-life learning of orthographic regularities was implicit, but that the observed transfer decrement runs against the idea of rule abstraction and supports the action of mechanisms that exploit statistical regularities of the material. The fact that the effect resided throughout the five years of training invalidates the argument that insufficient training causes the transfer decrement in laboratory studies, at least for the acquisition of orthographic rules.

Robinson (1997) examined the nature of second language learning. Contradicting Reber's (1989) notion of implicit rule abstraction, he stated that if the grammar is instructed explicitly, the rules will easily be generalized to new settings, whereas if the grammar is learned implicitly, it will be associated with the instances previously seen, and will be difficult to generalize to new settings. In Robinson's study, Japanese adults attempted to learn a grammar rule in English by following one of four learning programs: in the *implicit training* condition, instructions to memorize sentences were given. In the *incidental training* condition, participants were presented with grammatical sentences and follow-up questions that were supposed to cue them to the relevant features of the rule. In the *enhanced training* condition, the same questions were given, as well as further cues by highlighting the rule-relevant parts of the sentence. In the *instructed learning* condition, a brief explanation of the rule and written instructions were given. After training, all participants were instructed to classify previously seen and novel sentences as grammatical or ungrammatical. If implicit learning is an effective way of learning second language grammar, one would expect participants in the implicit training condition to be good at classifying both new and old sentences, and performance on new sentences to be as good as more explicitly instructed participants. Robinson found that on previously exposed sentences, all participants had high accuracy, and there were no differences between the training conditions. Presumably, all participants were equally able to store sentences in memory and to retrieve them at test. On novel sentences, however, explicitly instructed participants performed significantly better than other groups; moreover, participants in the enhanced training condition classified sentences more accurately than participants in the implicit training condition. Robinson concluded that implicit knowledge is memory based and has limited generalizability. Therefore, the best strategy for teaching language is to rely on explicit guidance. This is in accordance with Shanks and St. John's (1994) conclusion, after an extensive review of implicit learning studies, that the learning is either due to exemplar memory or due to explicit learning that has not been detected because the experimental procedures used to assess conscious awareness of rules or associations were not sensitive enough to detect fragmentary knowledge.

In sum, these two studies that addressed real-world applications of implicit learning did not support unconscious rule abstraction. Both Pacton et al. (2001) and Robinson (1997) presented findings that support a memory-based increase in performance on known instances, but participants were not able to transfer this knowledge to new sets of stimuli. The authors concluded that these findings contradict claims that implicit rule abstraction would be easier in a more realistic setting.

In the present study, we attempted to teach the atomic bonding rule to children who were not previously exposed to chemistry. There has been some interest in methods of teaching bonding rules in chemistry to students (see Fjeld & Voegtli, 2002), but to our knowledge, no study has examined implicit learning of atomic bonding rules.

The atomic bonding rule was chosen because it is a simple rule, previous exposure (both explicit and implicit) is unlikely, and it is a rule that will be taught on a later curriculum. Moreover, it extends the studies by Pacton et al. (2001) and of Robinson (1997) by using learning tasks outside the language domain. The stimuli presented in the experiments were graphic representations of chemical molecules, where the letters C, H and O represent carbon, hydrogen and oxygen atoms, respectively, and lines between the letters represent atomic bonds. The stimuli are structured by the rule for atomic bonding (Graham Solomons & Fryhle, 2003), which states that each type of atom must have a specific number of bonds to other atoms. For the presented molecules, the C atom has four bonds, the O atom has two and the H atom has one. The participants were considered to explicitly know the rule if they were able to state the rule in some form, to state some fragment of it (such as how many bonds one specific type of atom should have), or to give a correct example of its use.

After exposure to correct chemical molecules, the participants were told that the stimuli were structured by a rule, and asked to discriminate between correct and incorrect novel molecules. If participants performed significantly above a control group or above-chance level, one could assume that learning had occurred. Any learning – implicit or explicit – could be caused by both rule abstraction and retrieval of probabilistic information: participants could have abstracted the rule, and thus at some level would know how many bonds there should be to each type of atom. On the other hand, participants may have retrieved that they have been presented with molecules having four bonds for C atoms, but that they have never seen a C atom with three or with five bonds. This is a memory-based strategy, so participants do not need to abstract the rule in order to show above-chance performance.

In experiment 1a, we tested materials in order to assess whether the control group is at chance level; in addition, we examined implicit learning. In experiment 1b, we tested a larger sample with various training groups. In experiment 2, we attempted to replicate experiment 1b with a simpler set of stimuli.

All experiments were conducted in accordance with the ethical guidelines of the American Psychological Association; active informed consent from parents was required for children to participate.

2. Experiment 1a

The aim of this experiment was straightforward: can bonding rules in organic chemistry be taught by mere exposure of accurate chemical formula and without explicit instruction of the rules? To this purpose, we tested children who have never before been instructed about atomic bonding rules.

Experiment 1a was run to test our materials and procedure, and in order to establish a baseline to which later experiments would be compared. Moreover, it provided a first test of whether atomic bonding rules can be learned implicitly. An experimental group was trained on real molecules while a control group was trained on irrelevant visual stimuli. After training, both groups were asked to classify novel molecules as right or wrong. The classification performance of the experimental group was compared to that of the control group.

2.1. Method

2.1.1. Participants

Forty-four pupils from an elementary school participated in experiment 1a as part of their school day. The participants, 24 girls and 20 boys, were 11 or 12 years old. They attended the seventh year in the Norwegian school system, and were never before taught atomic bonding rules. They were randomly assigned to the experimental group or the control group, yielding 22 participants per group.

2.1.2. Materials

The experimental stimuli consisted of graphical representations of organic chemical molecules that represented real compounds. The images were created using Microsoft Paint, and were printed on A5 paper. The letters in the molecules were about 7 mm high. The molecules were composed of the atoms carbon, hydrogen, and oxygen, and had single, double and triple atomic bonds. Training molecules in the experimental group all followed the bonding rules for chemical molecules. The control group stimuli (see Fig. 1C for example) were Arab and Hebrew letters of roughly the same size as the molecules.

The training set consisted of 40 molecules and was divided into two sets, so that each participant saw 20 of the molecules in the training phase, and the other 20 in the test phase. The use of the two stimulus sets as training and test sets was counterbalanced across participants. The test stimuli consisted of 20 molecules that were not shown in training, randomly mixed with 20 incorrect versions of the same molecules. The incorrect molecules were created by either adding or removing three bonds to C atoms in the molecules; this resulted in additional or removed H atoms. Examples of correct (A) and incorrect molecules (B) are displayed in Fig. 1.

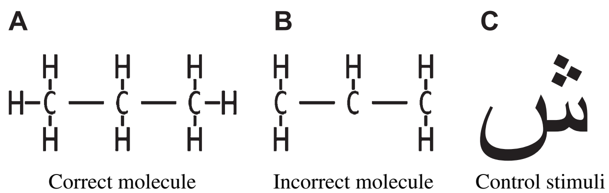

Fig. 1. Examples of correct and incorrect molecules and control group stimuli.

2.1.3. Procedure

Participants were tested in groups in a classroom setting. The experiment was conducted in the children's regular classroom as part of their school day. Instructions were given in verbal and written form. For the training task, the participants were given a booklet with one training stimulus on each page. Experiment group participants got pictures of correct molecules, while control group participants got Arab and Hebrew letters. All participants were instructed to examine closely each picture and try to remember it. The participants were given a verbal cue to turn the page every 15 s until all 20 pictures had been seen.

For the classification task, participants were given a new booklet that was similar for all participants. The first page stated that there are rules to how atoms can be combined to create molecules, and that one could tell if a molecule was right or wrong by checking if it conformed to the rule. We further instructed participants to mark a box for "right" or a box for "wrong" for each picture. The participants were encouraged not to worry if they did not know the rule, but to follow their feelings. The following pages contained correct and incorrect chemical molecules. The participants were given a verbal cue to turn the page every 15 s until all 40 pictures had been answered. At the end of the booklet, the participants were asked to write down what they thought the rule was or, failing that, which approach they had chosen to solve the task. Then, participants were thanked and carefully informed about the nature of atomic bonding rules.

2.2. Results and discussion

In experiment 1a, the experimental group trained on chemical formula performed slightly better than the control group trained on irrelevant stimuli, $M = 21.09$, $SD = 3.63$ versus $M = 20.64$, $SD = 2.30$, but this difference was not significant, $t\,(42) = .50$, $p = .62$, $r = .08$. Neither the mean of the experimental group, $t\,(21) = 1.41$, $p = .17$, $r = .29$, nor the mean of the control group, $t\,(21) = 1.30$, $p = .21$, $r = .27$, was significantly different from chance level. None of the participants in either of the groups were able to report the rule. These results indicate that participants who trained on relevant stimuli did not perform significantly better than participants who trained on irrelevant stimuli. Both groups in experiment 1a were neither able to learn the rule explicitly nor able to demonstrate implicit learning in the discrimination task. Further, since the means were not significantly above-chance level, chance level can be used as a comparison to check for effect of learning instead of a control group in experiment 1b. Perruchet and Reber (2003) proposed that when introducing a new type of experiment, one can run a control group to see if stimuli in the control condition are at chance level. If this is the case, then future experiments using the same training and test stimuli can be compared to chance level.

3. Experiment 1b

Experiment 1a yielded no evidence for implicit learning. However, the fact that the experimental group failed to differ significantly from the control group and from chance level may be due to an overly difficult training task. Indeed, participants were presented each training molecule for only 15 s, and did not perform a task that focused attention on the stimuli. Experiment 1b attempted to address these concerns by having four groups perform different tasks on the training stimuli, which were shown for 20 s; each task predicted to cue the participants' attention to the rule to different degrees. Participants in the *memorization group* were merely instructed to memorize the molecules. Participants in the *count atoms group* were asked to count all the atoms in each molecule, which was a somewhat more demanding task, but not directly relevant to the rule. Participants in the *count bonds group* counted the number of atomic bonds to the C atoms, which would always result in four bonds to each C atom, and should guide them to discover the rule. The participants in the *verify rule group* were told that each C atom is supposed to have four bonds, and were asked to check whether this rule was followed for each item. In the test phase, all four groups were instructed to classify accurate and inaccurate molecules. After classification, an explicit knowledge measurement was taken.

If the rule was too difficult to learn even with explicit instruction, we would observe no learning in any of the groups. If the rule can be learned implicitly through mere exposure, then all four groups would show high performance in the test phase, but explicit knowledge would only be present in the groups which receive instructions that cue the participants to the rule (count bonds group and verify rule group), while the participants who solved the task using implicit learning (memorization group and count atoms group) would show high performance without explicit learning. If we did not observe implicit learning, explicit knowledge would increase performance, and this would cause both measures to be high in the two conditions with instructions relevant to the rule (count bonds group and verify rule group) and both measures to be low in the two groups that were not given the opportunity to learn the rule explicitly (memorization group and count atoms group).

3.1. Method

3.1.1. Participants

Eighty-nine pupils from three different schools participated in experiment 1b as a part of their school day. The participants, 43 girls and 34 boys, were 11 and 12 years old. Twelve participants were excluded from analyses for lack of compliance to the training instructions; post-experiment analyses showed that they either failed to respond to the training task or appeared to have misunderstood the training task, leaving 77 participants for the main analyses. The participants were randomly divided into four experimental groups, and after removal of noncompliant participants, there were 20 participants in the memorization group, 22 participants in the count atoms group, 17 participants in the count bonds group and 18 participants in the verify rule group.[1]

3.1.2. Materials

All four groups received the same stimuli, but the instructions varied between groups. The training and test molecules for the experimental group of experiment 1a were used for all participants in experiment 1b.

3.1.3. Procedure

Participants were tested in classes of up to 18 pupils at a time. The testing was done in their regular classroom, as part of their regular school day. The four experimental conditions were represented about equally within each class. Instructions were given in both written and spoken form for the parts of the experiment where all participants had the same task; we used only the written form when the task differed between the experimental groups. Individual explanation was offered to participants who responded that they did not understand their task.

For the training task, the participants were given a booklet that on the first page had the written instructions for their respective group and an example of a molecule picture (this molecule was not used later in the experiment), followed by the training stimuli on the next pages, one picture on each page. The memorization group was instructed to examine each picture and try to remember it. The count atoms group was instructed to count all the letters in the picture. The count bonds group was instructed to count all the bonds to the C atoms. The verify rule group was explicitly told that all correct molecules should have four bonds to the C atom and was asked to check whether the rule was followed for each of the items. The participants were instructed to write the answer of the tasks on each page, except for the memorization group which was not required to provide a response. The participants were given a verbal cue to turn the page every 20 s until all 20 pictures had been seen.

For the classification task, participants were given the same booklet as in experiment 1a, with the exception that four questions had been added at the end.

Immediately after finishing the classification task, the participants were asked to answer four questions probing for explicit knowledge. The *Open Question* asked the participants to write down what they thought the rule was or how they had solved the task. In order to score on this measure, the participants had to describe the rule (“there should be a specific number of bonds to each type of atom”), give an example of its use (“the C atoms should always have four bonds”) or describe an invalidating fragment (“the molecule is incorrect when there are more than four bonds to the C”). The *Strategy Question* asked participants whether they had used the rule they described in the previous question, just guessed or used both rule and guessing when they classified the test molecules. In the *Rule Question*, participants had to choose which of five alternatives most closely matched the rule. The alternatives were (1) the shape of the picture, (2) whether the picture was similar on both sides, (3 – the correct alternative) the number of lines to each type of letter, (4) the number of letters in the molecule and (5) where on the sheet the elements were placed. Finally, in the *Molecule Question*, participants had to answer how many atomic bonds the atoms C, H and O, respectively, had in the correct molecules, and they were given alternatives from one to five bonds for each atom. The Open Question and the Molecule Question were used in subsequent analyses to distinguish learners from non-learners.

[1] Analyses in addition to those reported later in the article showed that exclusion of these participants did not change the main results and therefore did not change the conclusions.

3.2. Results and discussion

In experiment 1b, all participants were tested with relevant training stimuli, but they were given one of four different training tasks that − to an increasing extent − guided them to the rule. If participants showed only explicit learning, both performance and explicit knowledge should be high in the count bonds group and the verify rule group, and both performance score and explicit knowledge should be low in the memorization group and the count atoms group. If implicit learning occurred, the memorization group would have high task performance, but little explicit knowledge. We will first report the analyses according to experimental groups. Then the data will be reorganized according to the participants' scores on explicit knowledge measures.

The means, percentage correct, standard deviations, t-tests and effect sizes r (see Rosenthal, Rosnow, & Rubin, 2000) to chance level are shown in Table 1. A one-way ANOVA shows that group membership had a significant effect on classification (F (3, 73) = 22,08, $p < .001$). Considering the many t-tests performed in Table 1, an adjustment of the alpha level was performed to avoid the danger of acquiring a cumulative Type I error. According to the Holm's Sequentially Rejective Bonferroni Test (Keppel, 1991; Kirk, 1995), the modified alpha level was obtained by dividing the original alpha level (α) by the number of comparisons (C) for the largest t-value, or if, as in our case, sample sizes are not equal, for the largest p-value. For the second largest p-value, the modified α level is obtained by $\alpha/(C-1)$, for the third largest by $\alpha/(C-2)$, and so forth. This yielded corrected α levels, from the largest to the lowest p-value, of .0125, .0167, .025, and .05, respectively. At these α levels, all groups were significantly above-chance level. The effect sizes reveal that far higher performance scores were observed in the count bonds group and the verify rule group than in the memorization group and the count atoms group. A pairwise comparison between the two former and the two latter groups shows that this difference was statistically significant, t (75) = 8.00, $p < .001$. This suggests that participants given the opportunity to abstract the rule explicitly were able to do so, while those given the opportunity to learn the rule implicitly almost completely failed to do so.

This conclusion was bolstered by six pairwise comparisons between groups, using Holm's Sequentially Rejective Bonferroni Test with corrected α levels, from the largest to the lowest p-value of .0083, .01, .0125, .0167, .025, and .05, respectively. The memorization group did not significantly differ from the count atoms group (t (40) = .89, p = .380), and the count bonds group did not significantly differ from the verify rule group, (t (33) = −1.10, p = .280). Apart from that, all group comparisons yielded significant differences: memorization group to count bonds group (t (35) = −3.84, $p < .001$); memorization group to verify rule group (t (36) = −5.83, $p < .001$); count atoms group to count bonds group (t (37) = −5.41, $p < .001$); count atoms group to verify rule group (t (38) = −8.44, $p < .001$).

It is conceivable that some of the participants in the memorization group and the count atoms group managed to learn the rule without being given the cues that the count bonds group and the verify rule group received, and that some of the participants in the count bonds group and the verify rule group failed to learn the rule despite the cues they were given. Similar observations were made in other studies (e.g. in Shanks, Johnstone, & Staggs, 1997, experiment 4). Johnstone and Shanks (2001) divided participants into learners and non-learners based on the extent of reported explicit knowledge. We compiled the explicit knowledge measures in the questionnaire in order to make a strict criterion for deciding whether participants possessed explicit knowledge. In order to score on the compiled Explicit Knowledge criterion, participants needed to score on the Open Question as well as on the portion of the Molecule Question that addressed the number of bonds to the C atom, the correct answer being four. In addition, a No Explicit Knowledge criterion was compiled. In order to score on this criterion, participants needed to answer both of the questions above

Table 1
Experiment 1b groups' performance scores

	Count atoms group (n = 22)	Memorization group (n = 20)	Count bonds group (n = 17)	Verify rule group (n = 18)
Mean test performance	22.45	24.00	33.35	35.94
Standard deviation	4.33	6.74	8.09	5.77
t to chance level (20)	t (21) = 2.66	t (19) = 2.65	t (16) = 6.80	t (17) = 11.71
p to chance level	p = .014	p = .015	$p < .001$	$p < .001$
Effect size to chance level	r = .50	r = .52	r = .76	r = .94

incorrectly. We did not include the Strategy and the Rule Questions in the criteria, because reporting a certain strategy did not necessarily imply using that strategy, and the Rule Question did not provide additional information for those who reported the accurate rule in the Open Question. Across all participants, a group of 30 participants met the Explicit Knowledge criterion, 27 participants met the No Explicit Knowledge criterion and 20 participants were scored as having some intermediate state of explicit knowledge. The intermediate subjects were excluded from further analyses. Group membership had a strong effect on explicit knowledge. The distribution of participants' explicit knowledge according to the two criteria is displayed in Table 2.

Holm's Sequentially Rejective Bonferroni Test was performed for the comparison of the two groups with chance level, yielding a corrected α level of .025 for the larger p-value and .05 for the smaller. Explicit knowledge had a strong effect on performance: both groups were above-chance level, but the effect sizes differed markedly, $M = 37.10$, $SD = 3.41$, $t\ (29) = 27.49$, $p < .001$, $r = .98$ for the group with explicit knowledge; $M = 21.74$, $SD = 4.29$, $t\ (26) = 2.10$, $p = .044$, $r = .38$, for the group without explicit knowledge. This demonstrated implicit learning, as even participants without explicit knowledge showed above-chance accuracy. A t-test that compared the two groups revealed that explicit knowledge had a significant effect on classification ($t\ (55) = 15.03$, $p < .001$). Participants who did have explicit knowledge demonstrated higher performance than participants who did not explicitly abstract the rule.

In sum, the findings of this experiment suggest that the training tasks that explicitly focused on rule-relevant features led to high task performance. Furthermore, performance level was highly related to explicit knowledge. The memorization group and the count atoms group showed above-chance performance, indicating at least some implicit learning. However, the amount of implicit learning was too small to recommend the use of mere exposure to chemical formula in classroom settings for teaching atomic bonding rules.

The chemical compounds used in this experiment were relatively complex; we designed a second experiment with simpler compounds in order to examine whether this change results in better implicit learning.

4. Experiment 2

Experiment 1b indicated that cueing participants' attention to the rule-relevant aspects in the training stimuli was the most efficient approach, although we observed at least some implicit learning. The literature is unclear on whether implicit learning is most efficient with complex or with simple stimuli (see Perruchet & Vinter, 2002). Berry and Broadbent (1988), for instance, assumed that implicit learning in dynamic systems control tasks occurs when the situation is too complex to be solved strategically. In contrast, implicit sequence learning appears to be most pronounced with simple rather than complex sequences (e.g., Cohen, Ivry, & Keele, 1990). Therefore, experiment 2 was designed to replicate the observed effects with a less complex stimuli set from the same domain. The main question is whether simple chemical compounds yield an amount of implicit learning that renders non-guided stimulus exposure techniques in classroom settings advisable.

4.1. Method

4.1.1. Participants

Eighty-two pupils (39 girls and 41 boys; two pupils did not report their sex) participated in experiment 2 under the same conditions as in experiment 1b. The same exclusion criteria were used to exclude 11 participants, so that 71 participants entered statistical analyses.[2] The participants were randomly divided into five experimental groups; after removal of noncompliant participants there were 16 participants in the control group, 14 participants in the memorization group, 15 participants in the count atoms group, 13 participants in the count bonds group and 13 participants in the verify rule group.

4.1.2. Materials

The experimental groups were presented the same stimuli, but the instructions varied between groups. The control group had the same test stimuli as the four experimental groups and the same instructions as the memorization group,

[2] In addition, an entire class was excluded from analysis because one participant in the rule verification group told the rule aloud in class; as a consequence, most participants in this class showed high accuracy in the classification test. There were no such problems in the other classes.

Table 2
The distribution of experiment 1b participants according to explicit knowledge

	Count atoms group ($n = 22$)	Memorization group ($n = 20$)	Count bonds group ($n = 17$)	Verify rule group ($n = 18$)
Explicit knowledge criterion	1	2	12	15
Intermediate	8	5	4	3
No explicit knowledge criterion	13	13	1	0

but the training stimuli were the Hebrew and Arab letters used in experiment 1a. As the test stimuli differed from those in experiment 1a, we had to run a new control group in order to assess whether the performance of the groups in this experiment can be compared to chance level.

The training stimuli of the experimental groups and the test stimuli were similar to those from experiments 1a and 1b, but simpler, in the sense that they consisted of fewer atoms. Since all accurate molecules were carbon based, and all inaccurate molecules retained the same number of carbon atoms, the number of carbon atoms in each molecule can be used as a measure of stimulus complexity. In the new set, no molecules exceeded six C atoms, with an average of 3.4 C atoms per molecule, as opposed to the set used in experiment 1b, which had up to 12 C atoms in a molecule, and an average of six C atoms per molecule. In addition, there were no ring molecules, so all molecules had a chain structure (as the molecules in Fig. 1).

4.1.3. Procedure

The procedure was identical to experiment 1b. There were the same four groups as in experiment 1b, memorization, count atoms, count bonds and verify rule group, plus a control group, as in experiment 1a. The same measure of explicit knowledge was used as in experiment 1b.

4.2. Results and discussion

As in experiment 1b, analyses were run first by assigned group, then by the explicit knowledge criterion.

The means, percentage correct, standard deviations, *t*-tests and effect sizes *r* to chance level are shown in Table 3. A one-way ANOVA showed a significant effect of the training task on later performance (F (4, 66) = 32,40, $p < .001$). Holm's Sequentially Rejective Bonferroni Tests showed that memorization group, count bonds group, and verify rule group were significantly above-chance level, while control group and count atoms group were not. As in experiment 1a, the control group performance showed that chance level could be used as a baseline.

As in experiment 1b, some implicit learning could be observed for the memorization group only, but not for the count atoms group. A *t*-test (t (27) = 2.17, $p = .039$) revealed this difference to be significant. We can only speculate that the count atoms task may have distracted from implicitly learning the rules by using resources that would be needed for acquisition of the rule without awareness.

Using the same criteria as for experiment 1b, 17 participants in experiment 2 met the Explicit Knowledge criterion, 37 participants met the No Explicit Knowledge criterion and 17 participants had an intermediate state of knowledge (see Table 4). Despite being significantly above-chance level, all members of the memorization group met the No Explicit Knowledge criterion, suggesting that they learned implicitly. The participants who met the Explicit Knowledge criterion were above-chance level on performance ($M = 39.06$, SD = 1.60, t (16) = 49.12, $p < .001$, $r = .997$), as were

Table 3
Experiment 2 groups' performance scores

	Control group ($n = 16$)	Count atoms group ($n = 15$)	Memorization group ($n = 14$)	Count bonds group ($n = 13$)	Verify rule group ($n = 13$)
Mean test performance	21.06	21.80	24.93	32.54	38.00
Standard deviation	2.27	3.47	4.29	8.80	3.11
t to chance level (20)	t (15) = 1.88	t (14) = 2.01	t (13) = 4.30	t (12) = 5.14	t (12) = 20.87
p to chance level	$p = .080$	$p = .064$	$p < .001$	$p < .001$	$p < .001$
Effect size to chance level	$r = .44$	$r = .47$	$r = .77$	$r = .83$	$r = .99$

Table 4
The distribution of experiment 2 participants according to explicit knowledge

	Control group ($n = 16$)	Count atoms group ($n = 15$)	Memorization group ($n = 14$)	Count bonds group ($n = 13$)	Verify rule group ($n = 13$)
Explicit knowledge criterion	0	0	0	6	11
Intermediate	2	6	2	5	2
No explicit knowledge criterion	14	9	12	2	0

those who met the No Explicit Knowledge criterion ($M = 23.05$, SD = .68, $t\,(36) = 4.47$, $p < .001$, $r = .60$). Moreover, those who met the Explicit Knowledge criterion performed significantly better than those who met the No Explicit Knowledge criterion (t (52) = 15.30, $p < .001$).

We examined whether implicit learning could be improved when stimuli were simple. The memorization group learning complex formula in experiment 1b and the memorization group learning simple formula in experiment 2 were comparable in terms of presentation times. A t-test comparing them did not yield a significant result t (32) = .45. This post hoc comparison across experiments suggests that complexity of formula did not moderate the implicit learning effect.

5. General discussion

The main goal of this study was to examine if implicit learning, as reported by Reber (1967, 1993) can be replicated within an educational setting. To test this hypothesis, we studied the usefulness of implicit learning as an approach to teaching atomic bonding rules in chemistry. The general conclusion is that although some implicit learning could be demonstrated, explicit teaching was superior.

Experiment 1a compared participants exposed to real molecules with participants exposed to irrelevant stimuli on their subsequent ability to distinguish correct molecules from incorrect molecules. The group exposed to molecules failed to be significantly above the control group and above chance.

Experiments 1b and 2 replicated and extended this finding by comparing performance of participants trained in four different ways. The results show that even participants without explicit knowledge performed above-chance level. Remember that in experiment 1b, where we observed implicit learning, participants got longer training times – 20 s per item – than in experiment 1a, where no implicit learning could be observed. Groups that were provided with the rule or with a guided discovery task performed significantly better than groups that were given instructions that did not cue the rule. Furthermore, there was a strong effect of explicit knowledge on performance, suggesting that successful classification was due to an explicit understanding of the rule. In sum, providing cues on how to relate the molecules to consciously held rules resulted in much better learning than passive exposure to molecules.

The four different types of instructions in experiments 1b and 2 yielded different amounts of guidance towards the relevant features of the stimuli, thus providing the groups with different starting points for rule abstraction. While the memorization group and the count atoms group were not given any cues, the count bonds group was cued by counting molecules, and the verify rule group was cued by reading the rule. The results show that group membership had a clear influence on both performance and subsequent explicit knowledge. These results concur with the results of Robinson (1997), who found that a more explicit form of training was better suited for learning second language grammar.

Our results do not contribute to the theoretical debate between implicit rule abstraction and other, memory-based mechanisms. As mentioned earlier, the amount of implicit learning observed in our experiments could be explained by both mechanisms. This does not mean, however, that knowledge about the mechanisms that underlie implicit learning is unimportant. If we assume, for example, that learning is based on rule abstraction, the conclusions of what topics would profit most from implicit learning is different from the assumption that implicit learning is similarity-based or based on fragmentary knowledge. In the former case, we would predict that rule-based knowledge, such as laws of physics or atomic bonding rules, is best suited for learning from mere exposure of exemplars; in the latter case, more complex scenarios, such as the functioning of ecosystems or weather forecasting, where rules yield associative information between training and test items, may be more conducive for implicit learning techniques.

Taken together, the three experiments suggest that implicit learning is possible in an educational setting, but the magnitude of the effect is much lower than what can be achieved in the same time span with more explicit teaching strategies; this result reiterates findings on pure versus guided discovery learning (Mayer, 2004). On a theoretical level, it is noteworthy that implicit learning effects have been extended to atomic bonding rules. On a practical level, on the other hand, the use of mere exposure of chemical formula does not seem to be the most effective method to teach atomic bonding rules. However, our conditions may not have been optimal for implicit learning. A challenge for future research is to find conditions that render implicit learning more effective than in the experiments presented here. Directions for future research in instructional settings could include longer exposures during training, examination of implicit effects of participants' exposure to materials on subsequent explicit learning, or tests of different domains, such as ecology or weather forecasting.

It is important that alternative strategies of instruction are proposed. Techniques based on implicit learning research may one day play an important role in school curricula, but they need thorough empirical testing in order to prevent the introduction of ineffective or inefficient instructional tools (Anderson, Reder, & Simon, 2000; Mayer, 2004).

References

Anderson, J. R., Reder, L. M., & Simon, H. A. (2000). *Applications and misapplications of cognitive psychology to mathematics education*. Retrieved January 12, 2005, from http://www.educationreview.homestead.com/Math.html.

Berry, D. C., & Broadbent, D. E. (1984). On the relationship between task performance and associated verbalizable knowledge. *Quarterly Journal of Experimental Psychology*, *36*, 251–272.

Berry, D. C., & Broadbent, D. E. (1988). Interactive tasks and the implicit–explicit distinction. *British Journal of Psychology*, *79*(2), 251–272.

Cohen, A., Ivry, R. I., & Keele, S. W. (1990). Attention and structure in sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*(1), 17–30.

Dienes, Z., & Altman, G. (1997). Transfer of implicit knowledge across domains? How implicit and how abstract? In D. Berry (Ed.), *How implicit is implicit learning?* Oxford: Oxford University Press.

Dienes, Z., & Lounguet-Higgins, C. (2004). Can musical transformations be implicitly learned? *Cognitive Science*, *28*, 531–558.

Fjeld, M., & Voegtli, B. (2002). Augmented chemistry: An interactive educational workbench. Paper presented at the IEEE and ACM International Symposium of Mixed and Augmented Reality (ISMAR 2002).

Graham Solomons, T. W., & Fryhle, C. B. (2003). *Organic chemistry*. New York: Wiley.

Johnstone, T., & Shanks, D. R. (2001). Abstractionist and processing accounts of implicit learning. *Cognitive Psychology*, *42*(1), 61–112.

Keppel, G. (1991). *Design and analysis: A researcher's handbook*. Englewood Cliffs, NJ: Prentice Hall.

Kirk, R. E. (1995). *Experimental design: Procedures for the behavioral sciences* (3rd ed.). Pacific Grove, CA: Brooks/Cole.

Mayer, R. F. (2004). Should there be a three-strikes rule against pure discovery learning? The case for guided methods of instruction. *American Psychologist*, *59*, 14–19.

Pacton, S., Perruchet, P., Fayol, M., & Cleeremans, A. (2001). Implicit learning out of the lab: The case of orthographic regularities. *Journal of Experimental Psycholology: General*, *130*(3), 401–426.

Perruchet, P., & Pacteau, C. (1990). Synthetic grammar learning: Implicit rule abstraction or explicit fragmentary knowledge? *Journal of Experimental Psychology: General*, *119*(3), 264–275.

Perruchet, P., & Reber, R. (2003). Why untrained control groups provide invalid baselines: A reply to Dienes and Altmann. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *56A*(1), 125–130.

Perruchet, P., & Vinter, A. (2002). The self-organizing consciousness. *Behavioral and Brain Sciences*, *25*(3), 297–388.

Pothos, E. M., & Bailey, T. M. (2002). The role of similarity in artificial grammar learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 847–862.

Reber, A. S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning and Verbal Behavior*, *6*, 317–327.

Reber, A. S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General*, *118*(3), 219–235.

Reber, A. S. (1993). *Implicit learning and tacit knowledge: An essay on the cognitive unconscious*. London: Oxford University Press.

Robinson, P. (1997). Generalizability and automaticity of second language learning under implicit, incidental, enhanced, and instructed conditions. *Studies in Second Language Acquisition*, *19*, 223–247.

Rosenthal, R., Rosnow, R. L., & Rubin, D. B. (2000). *Contrasts and effect sizes in behavioral research: A correlational approach*. New York, NY: Cambridge University Press.

Shanks, D. R., Johnstone, T., & Staggs, L. (1997). Abstraction processes in artificial grammar learning. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *50A*(1), 216–252.

Shanks, D. R., & St. John, M. F. (1994). Characteristics of dissociable human learning systems. *Behavioral and Brain Sciences*, *17*(3), 367–447.

Tunney, R. J., & Altmann, G. T. M. (1999). The transfer effect in artificial grammar learning: Reappraising the evidence on the transfer of sequential dependencies. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*(5), 1322–1333.

Vokey, J. R., & Brooks, L. R. (1992). Salience of item knowledge in learning artificial grammars. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(2), 328–344.

Whittlesea, B. W., & Dorken, M. D. (1993). Incidentally, things in general are particularly determined: An episodic-processing account of implicit learning. *Journal of Experimental Psychology: General*, *122*(2), 227–248.