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The Effect of Knowledge Systematization on Learning Scientific Rules:

A Case Study Using a Qualitative Approach

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Abstract

Previous studies have revealed that learners have difficulty in applying rules they have already learned. We presumed that the reason for this was that they confused atypical examples with exceptions. To avoid this, this study aimed at enhancing knowledge systematization. To achieve this aim, a comparative rule was taught in addition to the target rule that was the learning objective. In a study session, four university students were engaged in collaborative learning. The teaching outcomes were examined by the participants' statements during the study session and interviews held eight months later. As a result, all participants applied the target rule to the atypical example in the study session, but only two explained the relationship between the two rules during the follow up interview. They were the ones that developed reasoning consistent with the knowledge system in the study session. The other two participants barely touched on the relationship and only mentioned a target example in the interview. This suggests that learners' cognitive activity, through which they trace relations represented in the system, is important for knowledge systematization.

Keywords: Knowledge systematization, rule learning, cognitive activity

School education provides many opportunities to learn general principles and laws (hereafter referred to as "rules"). Generally, learners are presented with rules and information on related examples by way of textbooks and teacher's instructions, and are expected to understand the rules based on given information. Prior study has demonstrated, however, that learners often fail to learn the rules (e.g., Magara, 1990; Kudo, 2003). Kudo (2003) taught university students the "seed plants rule," that is, "flowering plants produce seeds" using the example of tulips, and studied the way in which the learners interpreted this information and the extent to which rules are deemed applicable to generalizing. As a result, approximately 50% of the participants did not understand that the given information could be generally applicable to all seed plants. Moreover, the participants concerned had a tendency to restrict the application of the rules to plants that grow from bulbs such as tulips (over specification).

Indeed, the fact that we tend to learn by drawing on particular "examples" rather than information concerning generalized rules has been reported in fields of study such as inductive reasoning (LeFevre & Dixon, 1986) and analogies (Ross & Kilbane, 1997). However, it is a common practice for teachers to teach rules by explicitly explaining that rules have generality. Despite this, learners tend to apply rules only to examples discussed in the class and approximate examples. Why that is the case requires special mention. Thus far, various suggestions have been made in the following studies: the obstructive effects of naive concepts or misconceptions (Magara et al., 2006), learners' notion that rules may have some exceptions (Magara, 2006), the tendency to discount a range of instances (Fushimi & Magara, 2009), and insufficient abstraction of knowledge representations (Kudo, 2013). These studies share the common finding that the failure in rule learning is largely attributable to cognitive factors in the learner.

However, a new hypothesis, which is clearly distinct from past explanations, has been proposed. Nishibayashi (2016) pointed out the possibility of learners mistakenly interpreting "atypical examples" as "exceptions." Further, Nishibayashi asserted that such "confusion between atypical examples and exceptions" is caused by the fact that many attempts have been made to solely teach a single rule in previous studies. In dealing with a case in which we are unable to decide whether to apply rules or not, it is not possible to determine whether it is an "exception" or an "atypical example." For instance, after learning the rule that "flowering plants produce seeds," it is not necessarily the case that we immediately apply such a rule to plants without knowing about the presence of seeds, for there is a possibility that the plants concerned are an exception to the rule. Moreover, it is hard to assess the probability of the plants being exceptional by using the rule. Therefore, using a conservative estimate, the plant is likely to be considered as an exception rather than an example. By contrast, when multiple rules are interrelated in consistent relations, in other words, if "a knowledge system" exists, such confusion seems unlikely to occur. For instance, flowers are an organ for producing seeds. Seed plants certainly produce flowers. Therefore, plants that have separate means other than seeds (e.g., spores) do not produce flowers. By understanding that knowledge is correlated in such a way, it is natural to necessarily link the presence of flowers with that of seeds. As such, the hypothesis presented by Nishibayashi

(2016) not only presents a new perspective by attributing the failure of rule learning to the condition of rule teaching but is also significant in the practice of education as it suggests that the issue can be overcome through the construction of a knowledge system. The purpose of this study is to examine the hypothesis by Nishibayashi (2016). Thus, we adopted an educational intervention in the form of a small class discussion, which consisted of four students, and attempted to analyze in detail the processes of knowledge systematization on the basis of their remarks. In particular, we taught student participants not only the rule that was a target of our instruction but also several scientific rules in conjunction with it. We then investigated whether they could construct a knowledge system and apply the target rule to atypical examples.

Methods

Participants

Participants were recruited from a teacher training program for junior high schools. Four university students registered in the department of biological science who aspired to become science teachers participated in this study.

Procedure

A study session was arranged to teach rules concerning plants. At the session, one of the authors participated as a teacher and engaged in a teaching activity based on teaching materials that were prepared beforehand to facilitate rule learning. Teaching materials, consisting of a series of questions, photos, and comments, were presented to the participants using PowerPoint. The participants discussed relevant questions and expressed individual views. All the statements made during the session were recorded. The teacher engaged in prompting the participants to actively make remarks, without directing their discussion or providing them feedback on correct answers except in planned cases. The session lasted approximately 60 minutes. An interview was conducted with each participant after an interval of eight months following the study session.

Rules and Knowledge System

A target rule in this study is “land plants have roots, stems, and leaves.” Daikon radishes were used as a target example. As daikon radishes are atypical because their stems are hard to identify, they are easily misunderstood as exceptional plants without stems (see Figure 1). Thus, as pointed out by Nishibayashi (2016), it can be said that daikon radishes are an example of something that easily involves confusion between atypical examples and exceptions. To avoid such confusion, this study aimed to construct a knowledge system for participants (Figure 2). The knowledge system consists of the target rule, the comparative rule, and the basic rule. The comparative rule is “aquatic plants do not have roots, stems, or leaves.” Both the target rule and the comparative rule can be deduced from the basic rule. The basic rule concerns photosynthesis and the function of roots, stems, and leaves, which participating university students have already learned in science class at primary and junior high school. In this way, the framework of system construction is to relate the target rule to the comparative rule as well as to the already known basic rule. To draw an inference from the basic rule to the target rule and the comparative rule, however, what is needed is an “intermediary rule” concerning different conditions between land and aquatic environments, and the requirements of roots, stems, and leaves. To this end, intermediary rule A concerning land plants and intermediary rule B concerning aquatic plants were presented. Moreover, the relation between the target rule and the comparative rule is identical to the logical relation between the intermediary rules. This is equivalent to the converse of the contrapositive in logic, namely, the relationship between “p → q” and “not p → not q.” Needless to say, a proposition that is true in logic does not necessarily mean that the converse of the contrapositive is true. However, the veridicality of the rule of such a knowledge system is held as true even in the converse proposition, thus both a proposition and a converse of the contrapositive are true. Thus, the formation of a one rule group functions to guarantee the formation of the other rule group, making it possible to uniformly link morphological differences between land and aquatic plants based on growing environments, competition for survival, and adaptation to environments.

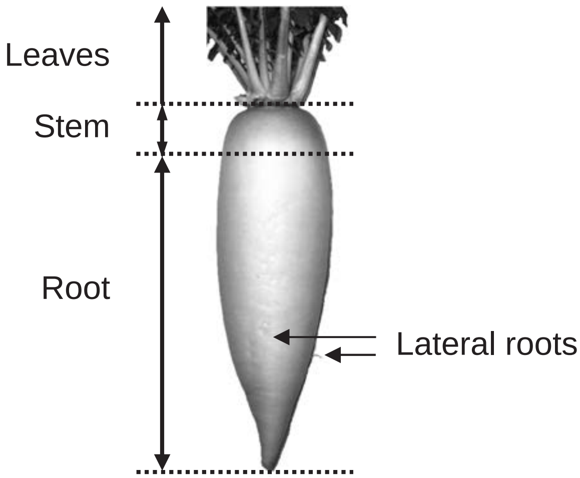

Figure 1. Daikon Radish (Many people think that daikon radishes do not have stems. The part between the leaves and the roots and the upper part of the roots are the stems of daikon radishes.)

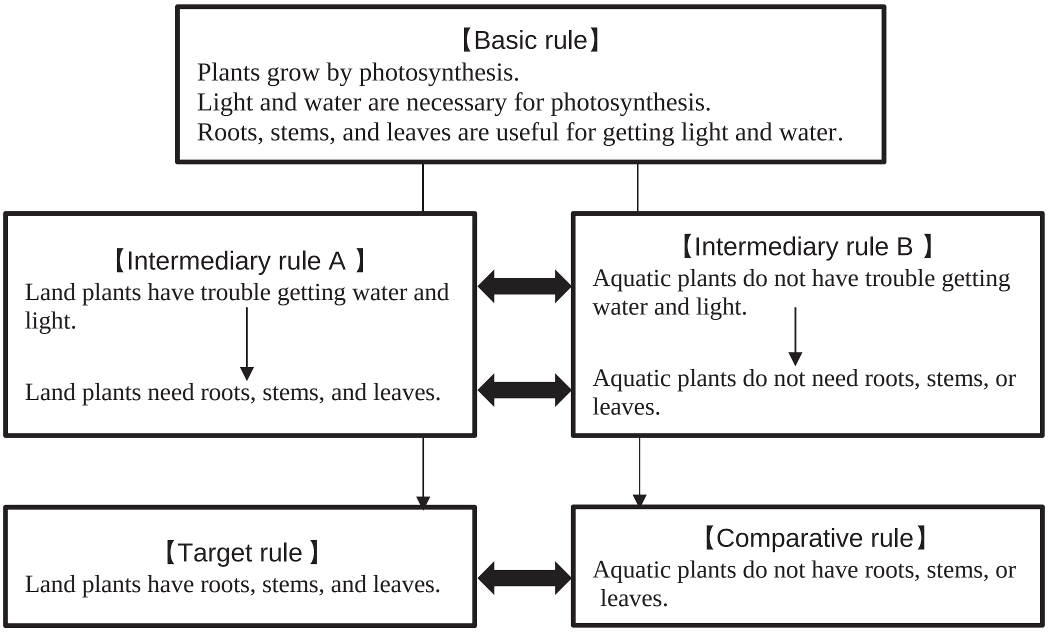

Figure 2. Knowledge system concerning roots, stems, and leaves.

Teaching Material

Teaching materials titled “Do daikon radishes have stems?” were provided to learn the target rule by taking an example of daikon radishes that at first glance do not appear to have stems. Table 1 displays the series of questions that constitute the teaching materials. Q1 reminds the participants of the rule that “plants have roots, stems, and leaves,” which was taught at primary school, and then asks if the rules would be applicable to all the plants. Q2—Q5 ask if the target example (daikon radishes) and dandelions have roots, stems, and leaves. Q6—Q12 are about each function of roots, stems, and leaves, which was also taught at primary and junior high school. Q13 and Q14 introduce marine algae as an example of the comparative rule. This is followed by reading material entitled “the topic of plant evolution,” which explicitly introduces the target rule and the comparative rule and describes a relationship among photosynthesis, the morphology of plants, and growing environments in the context of evolution. It was thereby expected that participants would constitute a knowledge system from these materials. From Q15 onward, the participants are required to apply knowledge acquired so far. Q15 and Q16 are about floating weeds and mosses that have properties somewhere between land and aquatic plants. Q17 and Q18 again take up dandelions and Q19 asks about daikon radishes once more.

In the study session or post-interview session, if learners referred to the relationship between the target rule and the comparative rule or the condition where the target rule is true compared to the comparative rule, we considered this to have demonstrated knowledge systematization.

Table 1. Teaching material on the series of questions, "Do daikon radishes have stems?"

Q1.	We learn in science class at primary school that "plants have roots, stems, and leaves." Does this rule apply to all the plants or not?
Q2.	This is a daikon radish. This is also a plant. Where are its roots, stems, and leaves?
Q3.	Daikon radishes are a type of plants. Do they not have roots, stems, and leaves?
Q4.	Is the green portion not a stem of daikon radishes?
Q5.	Do dandelions have stems?
Q6.	Let us think about the function of roots, stems, and leaves. What are leaves for?
Q7.	What are roots for?
Q8.	What are stems for?
Q9.	What is the benefit of stems growing tall?
Q10.	Trees grow tall by thickening and hardening stems, allowing them to unfold leaves high above other plants. In this way, by taking advantage of height, there are plants which adopted a strategy of easily winning the competition for light. What are they?
Q11.	What is the benefit of spreading roots?
Q12.	In what way are the functions of leaves, stems, and roots related to each other?
Q13.	Marine algae such as wakame seaweed, kelp, and sea lettuces are types of plants. They grow by photosynthesis like any other plants. By the way, do marine algae have roots, stems, and leaves?
Q14.	Marine algae do not have roots, stems, or leaves. How can they survive without them? (Topics on plant evolution)
Q15.	Floating weeds are plants that float on the surface of water. They look very different from land plants. They originally belonged to land plants called *satoimo* (taro) and have taken the shape they have through the process of evolution. Do floating weeds have roots, stems, and leaves? Let us think about the reasons for how plants of such a shape can survive.
Q16.	Aquatic plants are thought to have first appeared on land about 500 million years ago. Mosses and moss allies first started to grow on land. However, mosses and moss allies can survive only in damp and watery places even today. Why is that?
Q17.	Let us go back to the first question. Do dandelions have stems?
Q18.	Dandelions have stems. However, they are very short and cling tightly to the ground. In this way, they are defeated by taller plants in a competition for light. How do dandelions survive?
Q19.	Lastly, let me ask you a question once again. Do daikon radishes have stems? Where are they?

Results

Discussion among the Participants at the Teaching Session

Overview. In Q1, some plants, including daikon radishes as the target example, were considered as exceptions. In addition, some participants vaguely recognized that there were exceptions without being able to cite concrete examples. In Q2—Q4, the discussion evolved into the question of "whether daikon radishes have stems or not." As the discussion progressed, many attempted to explain that daikon radishes "do not have stems," while there were hardly any arguments about the assumption that they "have stems." In Q6—Q11, the participants, by and large, answered the question about the functions of roots, stems, and leaves correctly. However, in Q12, the participants struggled to respond to the question about how they are related. In Q13 and Q14, participants predominantly evaluated marine algae by its morphological characteristics rather than the functions of its roots, stems, and leaves. As the discussion progressed, two participants (participants A and B) started to make an inference by focusing on aquatic environments (discussed later). They continued to assert their reasoning from Q15 onward. Finally, in Q19, all the participants figured out that daikon radishes had stems and were able to specify parts that functioned as stems.

Quantitative analysis. Participants made 439 statements in the teaching session. Of all the statements, the percentages of each participant's statements were as follows. A: 38.0%, B: 39.0%, C: 5.7%, and D: 10.7% (Figure 3). Participants A and B accounted for 77%. There is a huge gap in assertiveness between A and B versus C and D during the discussion.

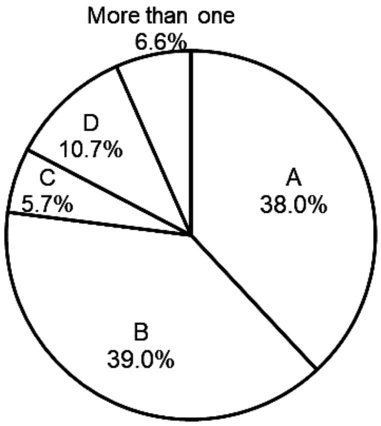

Figure 3. Percentages of number of each participant's statements.

Qualitative analysis. In this section, qualitative analysis is conducted on discussions about the comparative rule that is crucial to constructing the knowledge system. A record of statements, where applicable, is shown in Table 2. The participants discussed the question of whether marine algae have roots, stems, and leaves as cited in Q13. Based on the statements made by Participants A and B whose participation in the discussion was substantial, Table 3 illustrates characteristics of their reasoning in each phase of discussion. In phase 1, they mainly made an inference with a focus on the morphological characteristics of marine algae without making an inference from the function of roots, stems, and leaves, which had been addressed in the prior study session. What led the discussion to phase 2 onward was the statement made by the teacher who attempted to direct their attention to getting the water and light required for photosynthesis (T12, T13). In response to the statement, the participants came to understand that marine algae, which have no trouble getting water, would not need roots (A13, B9). Further, the participants spontaneously reviewed the conventional idea that "kelp has roots" and obtained a concept close to "rhizoids," namely, "something that may not function in absorbing water, but supports their own body" (A14). Taking the growing environments of marine algae into consideration in the subsequent phase 3, the participants noticed that marine algae had no trouble getting light, thus leaves would not be needed either. This led them to draw the conclusion in phase 4 that marine algae do not need roots, stems, or leaves (A23). Notably, the reasoning attained from phase 2 to phase 4 traced the flow from the basic rule to the comparative rule via intermediary rule B in the knowledge system (refer to Figure 2). In this way, the process of reasoning by Participants A and B was appropriate in light of the knowledge system. By contrast, the number of statements made by Participants C and D was low as they remained in the position of listeners to discussions between A and B. Yet, this does not mean that they did not participate in the discussion, but rather gave precise answers most of the time when asked by the teacher (C1, C2, D2). Also, they responded correctly when doing a final check of answers to questions (T26). Given these points, Participants C and D do not necessarily differ from A and B.

Table 2. A record of statements on the comparative rule during the study session

Q13.	Marine algae such as wakame seaweeds, kelp, and sea lettuces are plant allies, living by photosynthesis just like other plants. By the way, do marine algae have roots, stems, and leaves?
T1	Let me hear your view. Do you think marine algae have roots, stems, and leaves?
SS	Er・・・?
T2	This is kelp. These are sea lettuces.
A1	I think marine algae have roots, stems, and leaves.
T3	Is that so? You think marine algae also have roots, stems, and leaves, don't you?
S	I think kelp has them.
B1	Because wakame seaweeds have stems, do they?
A2	Er・・・? What about wakame seaweeds?
B2	(To Participant D) Are wakame seaweeds and "*mekabu*" the same thing?
D1	I wonder if the stem of wakame seaweeds is called "*mekabu*."
A3	Yes, that is so.
B3	Then, we can say that wakame seaweeds have stems, can't we?
A4	(To participants) Then, does kelp have roots, stems, and leaves?
SS	Well, kelp is…
A5	I think kelp has leaves.
T4	Oh, you think kelp also has leaves.
A6	I think kelp does have roots as well.
T5	Is that so? You think kelp has roots, too.
B4	What about sea lettuces?
T6	These are sea lettuces.
A7	Ah.
T7	Do sea lettuces have roots, stems, and leaves?
B5	I have not seen them other than those floating in the sea.
A8	Sea lettuces are lightly floating in water, aren't they?
T8	Yes, they are lightly floating in shallow water.
A9	I don't think sea lettuces have roots, stems, or leaves.
B6	I don't think that sea lettuces have roots, stems, or leaves either.

T9 You don't think sea lettuces appear to have distinctive features of roots, stems, or leaves. But you think kelp has such distinctions, correct? What do you think, Participant C?

C1 I have the same view.

T10 You think that kelp appears to have roots, stems, and leaves, but sea lettuces do not. Correct?

C2 Yes.

T11 What is your opinion, Participant D?

D2 Well, wakame seaweeds look like having roots, stems, and leaves. But, sea lettuces float in water. So, I doubt there are roots in the first place.

B7 I reckon that sea lettuces may be clinging to something to stay still.

S Sea lettuces lightly float in water.

A10 I have never seen it by itself, so I have no idea.

T12 Then, let's think about whether marine algae have trouble getting light.

SS Marine algae do not have trouble getting light.

T13 Isn't that right? Then, do they have trouble getting water?

A11 No, they don't.

T14 OK. What makes you think so?

A12 That is because they live in water.

B8 Because they live in water.

T15 OK. Taking a hint from these comments, do marine algae appear to have roots, stems, and leaves?

A13 They don't need roots.

B9 No need.

T16 It looks like they don't.

A14 But in case of kelp, it may need something to cling to the ground like roots, something that may not function in absorbing water, but to support their body.

T17 Ah, I see.

Q14. Marine algae do not have roots, stems, or leaves.

A15 Wow.

T18 You mentioned a while ago that kelp may need something to support their body. They are called rhizoids.

SS Ah…

T19 Kelp has something to lock their bodies, but they are not roots per se.

A16 I see.

B10 I see. Kelp is clinging to rocks, but it does not mean that it is absorbing nutrients from them. It is simply attached to rocks.

A17 It just clings to rocks.

(Continuation of Q14) Then, how can they survive without roots, stems, or leaves?

A18 Isn't it because of the function of roots, stems, and leaves?

T20 Oh, what functions of roots, stems, and leaves do you mean?

A19 Leaves absorb light and stems transport water and nutrients. But marine algae grow only in places with light from the beginning, don't they? Do marine algae also grow in the deep sea? Are they marine algae over there?

C3 I don't think they are marine algae.

B11 I don't think marine algae grow in the deep sea.

T21 Marine algae grow in a shallow sea.

B12 I have never seen them in the video.

A20 Sea snakes and others live there.

C4 Sea snakes are echinoderms.

A21 Sea snakes are different.

T22 Sea snakes are not plants, but animals.

A22 We are talking about the question of roots, stems, and leaves.

T23 I would like you to think about the hint given a while ago. Marine algae do not have trouble getting light, do they?

SS No, they do not.

B13	They have no trouble getting water, either.
T24	Yes, that's correct.
A23	Marine algae do not need roots, stems, or leaves.
B14	Because nutrients are available in water.
SS	No need.
T25	What you mean is that marine algae do not need to absorb nutrients from the soil.
A24	No need.
T26	Marine algae photosynthesize but do not have to compete with other plants for light or water. Assuming these facts, do marine algae need to make distinctions among roots, stems, and leaves?
SS	No.

Note. T: Statements by the teacher, A—D: Statements by each participant, S: Statements by participants (not otherwise specified), SS: Statements by more than one participant

Table 3. Changes in reasoning by Participant A and Participant B

The phase of discussion	Characteristics of reasoning	Result of reasoning
Phase 1	Judgment was made mainly on the basis of morphological characteristics of marine algae. No inference was drawn from the focus on the function of roots, stems, and leaves.	Wakame seaweeds have stems. (B1) Kelp has leaves and roots. (A5, A6) Sea lettuces do not have roots, stems, or leaves. (A9, B6)
Phase 2	Taking growing environments of marine algae into consideration, the result of reasoning about the presence of roots is reviewed.	Marine algae do not have trouble getting water. (A11) Marine algae do not need roots. (A13, B9) "Roots" of kelp are there to support their body. (A14, B10)
Phase 3	Taking growing environments of marine algae into consideration, the result of reasoning about the presence of leaves is reviewed.	Marine algae grow only in places with light. (A19)
Phase 4	Taking growing environments of marine algae into consideration, the result of reasoning about the presence of roots, stems, and leaves is reviewed.	Marine algae do not have roots, stems, or leaves. (A23)

Post-Interview Survey

An interview was conducted at an interval of eight months after the initial data collection to examine the retention rate of learning. In an interview, we asked about the details of the previous study session: (1) How the participants would respond this time around to the question, "Do daikon radishes have roots, stems, and leaves?," (2) How to better explain to those who think that "daikon radishes have no stems" and make them understand that they "have stems," (3) What points in the topic concerning aquatic plants were considered helpful in understanding daikon radishes, (4) Are there any other matters that left an impression? As a result, all the participants affirmed that daikon radishes "have roots, stems, and leaves" in (1) and retained the knowledge concerning the target example. By contrast, the participants commented differently on other questions. In (2), Participants A and B made statements that focused on the function of stems in photosynthesis, while Participants C and D did not give a similar sort of explanation. In (3), Participant A made systematic comparisons of the relation between the morphology of land plants, aquatic plants, and growing environments. He stated that he could understand the functions of roots, stems, and leaves more deeply by making a comparison with marine algae. Moreover, Participant B particularly referred to an example of floating weeds and evaluated marine algae as useful for making a comparison. By contrast, Participant C could not recall the very fact that aquatic plants were cited as a topic in the teaching session, while Participant D could not remember what topic concerning aquatic plants was discussed. Moreover, in (4), Participant A referred to the significance of comparing plants that have a different way of responding to environmental conditions and growing environments. Participant B directly referred to the target rule that "plants have roots, stems, and leaves in common." By contrast, the statements made by Participants C and D were limited mainly to target examples (see Table 4).

Table 4. Statements recorded in interview survey (4)

Participant A	It was quite remarkable to know that the whole body of daikon radishes are not roots, but are divided into stems and roots. Both floating weeds and marine algae are plants, but they have adapted to environments and evolved. This made sense. I thought it would be a good idea to compare not only land plants in general but also growing environments in order to deepen understanding.
Participant B	I had never seriously thought about daikon radishes or stems before. It was rather surprising to discuss the topic that daikon radishes naturally had stems. Also, it never occurred to me before that all the plants had roots, stems, and leaves in common as this topic seemed too familiar to ponder. After thinking about it again, I thought this made sense.
Participant C	Whether daikon radishes have stems, or marine algae have roots… You have just reminded me of that.
Participant D	Daikon radishes were the most impressive. I did not know which parts were stems or roots.

Discussion

The learning process and the outcome demonstrated various differences between Participants A and B versus C and D. The former not only proactively made statements but also developed reasoning that was consistent with the knowledge system in the study session. Further, in the interview they mentioned rules that were included in the knowledge system on multiple occasions. In light of this, it is assumed that A and B constructed a knowledge system by linking the rules of land plants and those of aquatic plants. By contrast, C and D were passive in regard to participating in the study sessions' discussions. Moreover, they hardly touched on rules and only mentioned a target example in the interview. They were also unable to recall the topic of aquatic plants discussed in the study session. In view of the above, the latter two students appear to have failed to accurately link the rule of aquatic plants with that of land plants, thus a knowledge system was not constructed.

Some points can be suggested from this study. The first point is the relation between the construction of a knowledge system and rule learning. Results of the interview show that Participants C and D did not even touch on a comparative rule or a target rule in their statements. In short, this suggests that if the construction of the knowledge system fails, what is attained is no more than example learning, which falls short of rule learning. Not only is this result consistent with findings in a prior study that rule learning often extends no further than learning examples (Kudo, 2003), but also with the hypothesis by Nishibayashi (2016) that the cause of failure in rule learning is attributable to learning conditions in which the construction of the knowledge system is not the aim and a single rule is taught. The second point is the condition of constructing a knowledge system. This study illustrated that a knowledge system cannot be constructed by passively learning a series of items that constitutes a knowledge system. Instead, it is necessary to proactively engage in more intensive cognitive activity during the learning process. This appears to be relevant to the finding that it is necessary to correlate knowledge and assimilate pre-existing knowledge to promote meaningful learning (Mayer, 2003). In particular, it is deemed important for learners themselves to trace relations represented in the system during the reasoning process in order to construct the knowledge system.

Some issues remain. First, what caused the participants to proactively engage in cognitive activity in a different way? Data obtained from the study did not clarify this point. Therefore, further study is needed. Moreover, the cognitive activity observed in the study was mostly spontaneous. Is the spontaneity indispensable for constructing a knowledge system, or would cognitive activity induced by the teacher have a similar effect? It appears necessary to examine these issues from the perspective of learning theory as well as in practice. Data collected in the study were obtained from the study session and an interview survey by sampling a small number of participants. The generality of the study result needs to be examined in future research.

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