Tools and Task Structures in Modeling Balance Beam

Ji Shen, Department of Physics, Washington University in St. Louis,
One Brookings Drive, St. Louis, MO 63130, Email: jishen@wustl.edu

Abstract: In the study I investigated the role of tools and task structures for science teachers of K-8 on the topic of balance in a professional development course. The findings show that the teachers tended to generate an additive rule, which is limited and contextualized, of balance condition, and failed to incorporate the more general multiplicative rule when thinking about balance. The study also shows that the teachers had difficulty in grasping a mathematical formula of balance condition. The learning outcome was partly a natural result of the materials the teachers used and the tasks they carried out. I conclude that learning tools and instructional tasks provide opportunities for understanding science content, but the understanding is confined to the tools and tasks employed.

Introduction

While much research has been devoted to the area of how learners think or manipulate materials under certain context, how learning materials contribute to learning processes and how learners appropriate energy in minds-on or hands-on, less attention has been paid to examining the structure of learning tools and the characteristics of learning tasks and their consequences in learning. Educators often advocate for providing a rich set of activities with hands-on materials, and are aware these activities will not necessarily lead to conceptual growth (Carter, Westbrook, & Thompkins, 1999; Lazarowitz & Tamir, 1994). But the mechanism of the constraints of such activities and the nuances of the advantages are not carefully investigated.

In the paper I will investigate the structure and characteristics of tools (hands-on materials or mathematical objects) and task structures (sequence and contents of tasks) and how they influence the learning processes for science teachers of K-8 in a professional development program at Washington University. On the one hand, I will focus on the conceptual growth of the teachers, especially two teachers, on the topic of balance based on assessments and class conversations; on the other hand, I will examine step by step the linkage between the teachers' conceptual progression and their manipulation with the balance beams.

Theoretical Framework

Vygotsky (1978) extended the notion of mediation of tools to signs (language in particular), which are an embodiment of the historical development of human society. He (1978) discussed the interaction between humankind and environment (natural and social) and its consequence in intellectual development. The main arguments focused on the genetic priority of language over thought in children's early intellectual development, which was a counter argument of Piaget (1970)'s genetic epistemology. Categorizing both in mediated activity, Vygotsky (1978, chap.4) distinguished signs from tools: tools are used to influence or change the external environment—there are consequences in psychological development though—while signs are used to control one's psychological behavior. In addition, signs are inherently societal, since they bear the purpose of human communication.

The distinction of sings from physical tools is important for theoretical discussion, but not the focus of the paper. I name both types of mediation—physical tools and abstract signs—tools. By definition, any object that is used with certain purpose is a tool. In hands-on activities, the tools include concrete materials; in minds-on processes, the tools include mathematical symbols and other abstract forms of representations. Tools are used to mediate higher level psychological functions. Any mediated learning is liberated through and confined by the tools that are utilized.

Another theoretical line in science education following Vygotsky's work is the Activity Theory (Engestrom, 1987, , 1999). The relationships among subjects, instruments, rules, community, division of labor and objects (activities) are depicted in the activity theory (Engestrom, 1999). A fundamental commitment of Activity Theory is that learning is essentially a social process. The internalization of mediating tools and signs is a vehicle to communicate with one's social community and natural environment. A problem is that internalization being realized, how creation and externalization can take place (Engestrom, 1999).

While acknowledging a broader social aspect of the learning activities (e.g., social interactions such as discourse among learners and instructors), in this paper I will put my primary focus only on the role of tools and task structures, which are elements of activities, in teachers' conceptual development of balance. I will examine how the task structures, proposed by instructors and symbolized social input, were internalized by the teachers. Also I will examine in the process of fulfilling the social expectations, how variations were carried on by the teachers.

Methodology and Research Context

Context

The data of the paper was extracted from a course for science teachers of K-8 on force and motion. The course is one of many courses which are a part of a continuing education certificate program in elementary science education and of a more extensive program leading to a master's degree in elementary science education. The course was 15 weeks long for 2.5 hours per week. Sixteen teachers were enrolled in the course (3 male and 13 female; 3 African-Americans, 1 Asian-American and 12 Caucasians). The average age of the teachers was 42.1 yrs (Std=12.4). The average years of teaching experience was 13.1 yrs (Std=12.1). There were three instructors, Jack, Pat, and Ann for the course who had been co-taught for about ten years. Pat was a professor at the department of physics, Jack was an experienced teacher and Ann was a science coordinator for a school district. As a team, the instructors believe there are two important aspects in learning science. (1) Learners are expected to understand the meaning of the operational definitions of scientific words. Therefore external physical reality is the key to inter-subjective understandings. (2) To bridge the understanding of complicated situations, learners build upon what they have experienced or can understand. In this, learning is a process of self-construction. The instructors carefully selected hands-on activities, aligned modules with the National Science Education Standards (National Research Council, 1996) and the state standards, implement research-based assessments, and emphasized the storyline of the physics content (Shen, Gibbons, Wiegers, & McMahon, 2005).

Data Collection and Analysis

The study used multiple sources of data. (1) With the consent of the teachers, I videotaped and took field-notes for each class. (2) During the course, pre- and post-assessments and three formative assessments were administered (only the first formative assessment was related to this paper). A coding system for the teachers was used to ensure that the results of the tests did not affect the final grades of the teachers and to protect the anonymity during the class discussion on the results of the tests. (3) Each teacher was required to write a journal every week, and all the teachers' journals were photocopied at the beginning of the class every week.

The study primarily focused on two teachers, Cindy and Kathy, since they were articulate and the focus of the camera. Their actions and conversations were recorded, which helped me understand how they made progress in understanding the concept of balance. Also, the results of formative assessment were analyzed, which reflected the common understanding of the whole class. The results of the class showed that Cindy and Kathy's understanding was not rare.

An appropriate unit of analysis is critically important and closely related to one's theory. For examples, Piaget chose schema, Vygotsky chose word meaning, and Wertsch chose mediated action (Wertsch, 1991). The unit of analysis of this study is a concept. A concept is not necessarily individualistic. It might be across individuals. Since I only focused on the concept of balance, all the data were extracted if they were related to the topic. This topic of balance spanned the first few weeks of the course. The videotapes on the topic of balance were all transcribed. The journals that were related to balance were compiled together.

Data and Findings

In the activity of balance beam, I will show (1) the progress of the teachers' understanding about the beam-balance, (2) the role of tool in learning, and (3) the role of task in learning.

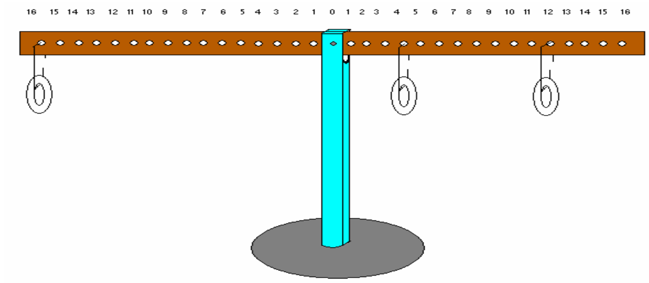

Figure 1. The beam balance used in the course.

Each set of the equipment included a pegboard beam with holes punched on it with equal distance (see Figure 1), a wooden base and support, screws that can mount them together, several washers, some paper clips. The purpose of the activity of the beam balance is for the teachers to be able to (1) balance a pegboard beam without trail-and-error, and (2) achieve the objective understanding: *the lever would balance if the product of mass and its horizontal distance to fulcrum was the same on both sides* (the *multiplicative rule*).

Step 1: One washer on one side, two washers on the other.

At first, Jack, one instructor, demonstrated how he balanced the beam with one washer on the left side at the 16^{th} hole and two washers on the right side at the 5^{th} and 11^{th} hole, respectively. Then with the left side untouched, the teachers were asked to find as many re-arrangements for the right hand side that would balance. The first round of data is 2,14; 3,13; 2,15; etc., and the data were recorded in a table on the blackboard by the instructors. The teachers recognized the pattern of the data quickly: the sum of the positions (or the numbers of holes) of the two washers on the right side equals the position of the washer on the left side—the additive rule. The general rule was a natural result of the task designed, for the pattern was easily discerned and the data table well presented.

One observation was that some teachers did not abstract the variables, distance, but merely counting the number of holes. For example Nicole summarized, "what was on the right, mathematically, equaled the left." It is a strong signal that teachers like Nicole did not explicitly model the variable of distance. Nicole merely referred to the invariant quantity as mathematical number. Some other teachers referred to the general rule as counting holes (see the section *formative assessment*).

Step 2: Two washers on one side, three washers on the other.

The new challenge was to put two washers on the left at the 8^{th} hole, then take three washers on the right side to balance the beam. The intension was that the teachers were able to induce the multiplicative rule. For example, if one puts two washers at the 5^{th} hole and one washers at the 6^{th} hole on the right side, it would balance the two washers on the left. And the equation would write as $Left : 2 \times 8 = 2 \times 5 + 6 : Right$

However, Cindy and Kathy's approach illustrated that many teachers still employed the additive rule. They balanced the beam by the combination of 2, 4 and 10 and 3, 5, and 7, and 4, 5, and 6. Cindy immediately noticed that they had the recent two combinations with a sum of 15 and the first combination with a sum of 16. Cindy suggested Kathy to redo the first trial to see if 15 would be a better choice—being consistent with the last two trials. They tried out the combination of 2, 4 and 9, as Kathy calculated. It worked: Kathy claimed that the beam worked with 16 for the left side and 15 for the right side. As a conclusion, Kathy summarized "On this [left] side, our distance, we have the 16 holes, in order to make it balance, we can only go about a distance of 15 holes on this [right] side."

In the first step, some teacher did not model the variable of distance (and the results of the formative assessment will show that it was a common case). Their conception is based on the concrete experience of counting holes. I do not think it is that trivial. Distance can be measured in various ways: counting holes with equal intervals, using meter sticks, using one's feet. Each provides an instantiation of the concept of distance, but none of them can fully capture the concept of distance. When experiencing the measurements of certain variables, the learner should explicitly associate the measurement with the variable. In the second step, Cindy and Cathy did model the variable of distance, but none of them paid attention to the mass of the washer. This was the case for the majority. I will argue later that this result was embedded in the equipment setup. It was also the result of the design of the task order. Since in the first step the teachers had already come up with the additive rule, in later steps they merely tried to apply the additive rule they generated to new situations. The additive rule worked with most teachers (some variation with Kathy and Cindy).

Another interesting point was that Cindy and Kathy found in their equipment that the balance worked in an odd way: the sum of the holes for the right side should be one less than that for the left side (henceforth the one-less rule). This finding was due to the beam-balance they were using. According to their conversation later, Cindy and Kathy knew that the balance was supposed to have equal sums for both sides. It was evident that their choice to stick with the one-less rule was because they were seeking the rule for their own balance equipment, not balance scales in general. A general pattern for them only meant a rule induced from the specific activity they did.

Step 3: Three washers on one side.

The first two tasks were posed by the instructors. Now Cindy and Kathy wondered if this rule worked when they put three washers on the left side at 8—a new task posed by themselves. Cindy predicted that they needed *four* washers at holes that added up to 15 to balance since in their last trials they had *three* washers at holes that added up to 15 on the right side. This reasoning was based on the two configurations they had done as shown in the Table 1. The prediction was sound: on the left side, the number of washers that was set increased from one, two to three; on the right side, the number of washers increased from two, three to four and the sum of holes was kept as 15. But Cindy did not notice the sum of holes on the left side had changed. This was because she did not do the calculation in their previous trials—Kathy did—and therefore she did not pay much attention to it.

Table 1. Cindy's prediction for the right side based on step 1 and 2.

Step	Left Side		Right Side	
	# of Washers	Sum of holes	# of Washers	Sum of holes
1- data	1 (at 16)	16	2	15
2- data	2 (at 8, 8)	16	3	15
3- Prediction	3 (Kathy: at 8, 8, 8) 3 (Cindy: not clear)	-	4	15

Kathy was aware that the sum of the holes on left side had changed. She reminded Cindy that if they added one more washer, the sum of holes on the left side was going to be 24. Cindy agreed and predicted immediately that on the right side the sum should be 23, according to the one-less rule they produced previously.

The negotiation of the task was not over yet. Cindy was unhappy about Kathy's plan of hanging three washers on the left side at the 8th hole. She noticed that Jack first hung one washer on 16, then two washers on 8. The position was in half while the sum was still 16. So the impression was in the next step they ought to use (1) the 4th hole (position in half) with (2) a number of washers that gave the sum of 16 (sum in constant) (see Table 2). Kathy did not agree that they should keep the sum as constant. She reasoned that the number of washers should increase one on each time, hence the current step should use three washers. Unfortunately, it was not possible for them to "do three into 16." That is, if sticking with Cindy's condition that the sum should be kept as 16, Kathy got 16/3 as the position of the hole. This was not an integer, hence not applicable to the equipment as given—the holes were already punched—unless they were not using the holes to hang washers. Cindy gave in and agreed to carry out Kathy's original plan, hanging three washers at the 8th hole.

Table 2. Proposed task for next step based on step 1 and 2.

Step	Left Side		
	# of Washers	Position of hole	Sum of holes
1	1	16	16
2	2	8	16
3 (Kathy's)	3	16/3	16
3 (Cindy's)	4	4	16

Having reached an agreement about hanging three washers at the 8th hole on the left side as the next step, Cindy and Kathy first tried the configuration 15, 5, and 4 (sum=24) on the right side and it was balanced. Cindy moved the washer from 15 to 14, it was still balanced. Inspired by this move, they tried a combination of 12, 6, and 5 (sum=23). Again, this confirmed what they found in the previous step that the sum on the right side should be one less than the sum on the left side.

In the three steps, we see how the equipments brought benefits (learn the rule that regulates the beam balance) as well as constraints. In particular, they influenced the generalizations and subsequent models in the following way. (1) When Kathy wanted to do three washers with a sum of 16, she found it not possible (unless they just hung it on the beam, not at any holes). This was because the holes on the beam were already punched, which limited the choices of the positions of the washers. (2) The one-less rule they induced was highly affected by their balance beam. Because of the limited precision of the balance, one was not able to discern the variance of a one-hole movement. (3) The additive rule was induced mostly because of the unit mass they were using, which in effect made weight an invisible variable functioning in units of one.

Also, we see that the task structures naturally shaped the learning outcome. In the first step, the task was fairly easy and the teachers generated the additive rule quickly. In the following steps, the teachers just applied what they had found out. Since Cindy and Kathy had an amendment of their first rule (right side has to be one less) because of the tool they employed, in the last step, they tried to test the revised additive rule. The expected multiplicative rule was not generated. Though the instructors hoped that the setup of the second step would elicit the multiplicative rule, the previous step had blueprinted the outcome.

Step 4: Summarizing.

Nonetheless, Kathy introduced multiplication in her summarization. But Cindy reminded Kathy the additive rule was the more basic rule for them according to the activity. Here they argued:

Kathy: Hole *times* washer
Cindy: It's the number of the washers *times*
Kathy: The hole they're in, *times* the hole that they're in.
Cindy: No, it's *not times* the hole they're in, cuz that only works at, the *total*, (Kathy: It's the *total*) the *total* of the holes they're in,
Kathy: The *total* of holes on right, on left,
Cindy: It's the *total* of the holes, yeah washers are in,
Kathy: Equals *total*, equals, is
Cindy: Is *total* going to be one more,
Kathy: Yes, that's going to be one more, the *total* on the left

The use of the term of "times" was shifted to "total" after Cindy pointed out that the additive rule was more generally applicable. The multiplicative rule was only needed in the situations where more than one washer was hung on the same hole. The general rule, the multiplicative rule, was a "special" case for them.

The additive rule arises naturally from the equipment used. The activity employs washers (with the same size and mass) as standard units of weight, hence in the formula of the general rule for the beam balance the mass of the washers can be cancelled out as shown below.[7]

$$\textit{left}: m_1 \times d_1 + m_2 \times d_2 + ... = \textit{right}: m_1 \times d_1 + m_2 \times d_2 + ...$$
$$\text{since } \textit{left}: m_1 = m_2 = ... = m = \textit{right}: m_1 = m_2 = ...$$
$$\Rightarrow \textit{left}: d_1 + d_2 + ... = \textit{right}: d_1 + d_2 + ...$$

Therefore, in this activity the multiplicative rule is equivalent to the additive rule. But the additive rule was more straightforward. Especially, after the first step when the additive rule was induced, the teachers held on it and applied it for different configurations.

Formative Assessment

The first question of formative assessment 1 (two weeks later) asked "what is your general rule?" All the teachers who stated their general rules mentioned the word "equal"—they understood there was an invariant involved. Table 3 summarizes the teachers' responses to the second part in question one.

Table 3. Teachers' responses to formative assessment 1.

The variable whose sum should be equal	Number of teachers
Number (of holes)	5
Distance (from fulcrum)	4
Weight	1
Mass and distance	2
N/A	4

No one indicated that the conserved variable was the sum of the product of each mass and its distance. Therefore, the objective understanding of the unit was not reached for the class.

Discussions

Achievement notwithstanding, the objective understanding, *the lever would balance if the product of mass and its horizontal distance to fulcrum was the same on both sides* (the *multiplicative rule*), has not been reached by most teachers. In the following discussion, I will explain why this is the case by two types of barriers.

Internal Barrier

There are two types of barriers in the activity: internal and external with respect to the activity. The internal barriers have the tendency to prevent any individual from succeeding; it is inherently embedded in the activity. The external barriers are generated by the learners; it is outside of the activity. In real learning processes, these two types of barriers often occur concurrently and are hard to distinguish.

The internal problem has two parts. The first part arises from the equipment used in a task. The activity employs washers as standard units of weight, hence in the formula of the general rule for the beam balance the mass of the washers can be factored out as shown in the section *Step 4: Summarizing*. Therefore, in this activity the multiplicative rule is mathematically equivalent to the additive rule. In fact, some teachers thought the additive rule was more general than the multiplicative rule because they did not model the variable of mass. The second part of the internal barrier is the task structure. In fact, when the instructors posed the second task (step 2), they asked the teachers to set two washers on one side and to hang three washers on the other to balance the beam. If the two washers were hang on a position that the sum of the positions of the two washers could be divided exactly by 3, say, the 6th hole (sum=12) instead of the 8th hole (sum=16), then the teachers would be able to hang three washers on the other side in one hole, say the 4th hole. This amendment could allow the teachers to induce a rule closer to the multiplicative one because they could summarize the data in a form as: 2(weight) x 6(position) = 3 (weight) x 4 (position).

External Barrier

The external barrier is external to the task but closely related to the learners. Again there are two parts in the external barrier. The first aspect lies in the way the learners manipulate the objects. This is of course closely connected with the mental states of the learners and with the internal barriers of the activity. But even with the right thoughts and appropriate equipment, there are still problems of manipulation. Mostly, these are just mal-manipulation and somewhat accidental. For example, errors in mathematical calculation, not full implementation of a plan, etc.

The other aspect of the external problem lies in representation. For the multiplicative rule, if one uses sentences, it is really laborious to remember. Additionally, there is a problem of unpacking an abstract representation. In the beam balance activity, one instructor, Pat, also provided a compact formula, $\sum_{i}^{left} m_i \cdot d_i = \sum_{j}^{right} m_j \cdot d_j$ without explaining the formula in detail. When applying the formula, some teachers calculated incorrectly: instead of calculating the products for each mass and then adding them together finally, they added all the masses together and added all the distance together and then multiplied the two sums. The result of the calculation contradicted their experimental data and the teachers were confused. In brief, the teachers have difficulties in unpacking the compacted formula.

In summary, the internal barriers include the materials and the structure of activities; the external barriers include the way subjects carry out the activity and the way the subjects represent (or read the representation) their knowledge.

Conclusion

In the paper, I examined the progress and difficulties of the teachers of K-8 in manipulating beam-balance and understanding the concept of balance in a force and motion course. The following problems were found in the balance activity. (1) Because of the hands-on experience with the balance activity, teachers' general rules rely heavily on the contextualized situation—counting holes. The variable of distance is not modeled. For some teachers, the referent of their general rule was referred to the particular balance scale they used. A general referent was not in consideration. (2) Due to the setup of the activity (equipment and task), teachers' general rules are bonded with the additive rule instead of the more general multiplicative rule. The variable of weight is not modeled. (3) Teachers have not mastered a compact mathematical formula. The succinct mathematical model is not mastered. I argue that these difficulties will keep arising if the role of the tools is not carefully investigated.

At a more general level, I have shown the ways of which the tools and tasks used in the balance activity provided both advantages and constraints. I propose that the learning tools, hands-on materials or minds-on equations, and the instructional tasks can either assist or constrain learning. That is, hands-on experience provides the concrete grasp of the concepts developed, but the objects of the hands-on experience might limit the learning with the concreteness. High level representation liberates learners from concrete and contextualized situations when they conduct abstract thinking, but the unfamiliarity with the objects of the higher level representation might prevent leaner from understanding the basic meaning.

The intention of the paper is not to provoke the reader to think ways to fix the instruction in this particular case—change the task structure, use different tools. I believe there must be better ways to do the instruction. My concern is more about learning in general. Since the advantages and constraints are inherently bonded with the tools and task structures, each time when one introduces new ways to fix an unsuccessful instruction, one introduces new constraints. Therefore, I suggest that in any science inquiry activities, the properties of learning tools and the structure of tasks be examined carefully. We should not assume that learners have acquired the necessary skills of using learning tools, nor shall we assume that learning tasks that we designed lead to the objective understandings automatically. I believe that a high level of awareness of the structure of tasks and characteristics of tools will free learners from the inherent limitations of the activities.

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