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Students' Perceptions and Designs of Simple Control Systems

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Abstract — *This study examines students conceptions and designs of simple control systems. A framework is presented that characterizes the cognitive models generated by the students for simple opening/closing systems in terms of an increasing differentiation of both structural and functional aspects of the systems: from an undifferentiated general input/output model, up to a complete causal model. The students' conceptions, missing conceptions, and misconceptions of the control systems are described and analyzed at three main levels: device knowledge, perception of the control process, and perception of information-flow within the system. The implications of this study are discussed for the learning of technological concepts, the instructional use of building and programming kits (e.g., Lego-Logo), and our research agenda. Copyright © 1996 Elsevier Science Ltd*

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This study is aimed at understanding students' perception and design of simple control systems. Control theory and models have been adopted by researchers and practitioners from a wide range of disciplines as conceptual frameworks for the understanding and description of natural and social phenomena (Doebelin, 1985; Parsegian, 1972). Countless examples of control mechanisms can be found throughout the natural, social, and artificial environments we are part of, from feedback mechanisms in our body, control mechanisms in tools and machines, to regulatory, adaptive, and evolutionary processes in nature. However pervasive outside school, these control concepts have yet to find their appropriate way into the science and technology curriculum. In addition, the ways students conceive, acquire, and apply control-related concepts and skills have yet to be comprehensively studied.

A first step in our research agenda, this study focuses on students' work on a particular kind of controlled system focusing on opening/closing mechanisms (such as elevator doors and drawbridges) within the Lego-Logo learning environment. The main questions we address concern the students' naive models of opening/closing mechanisms and the way these models evolve as a result of their repeated utilization in different learning situations. We will focus on:

1. *Perception of the control process.* What kind of models of simple control systems do students generate both naturally and within the context of varied instructional tasks?
2. *Device knowledge.* What conceptions, missing conceptions, and misconceptions of structural and functional aspects of the control systems do the student models reflect?

BACKGROUND

A person's mental model of a system becomes relevant across the spectrum of interactions with the system, whether the person is trying to understand the system (diSessa, 1983; Hegarty, 1988), predict its behavior (de Kleer & Brown, 1983; Williams, Holland, & Stevens, 1983), operate it (Kieras & Bovair, 1984; Stigler, 1984), repair it (Lajoie & Lesgold, 1989; Sanderson & Murtagh, 1990), or design a new one (Moray & Reeves, 1987; White & Frederiksen, 1986).

Several studies have been conducted regarding the role of mental models in professional training, such as operating procedures for communication devices (Matsuo, Matsui, & Tokunaga, 1991), pilots' instrument scanning abilities (Hameluck, 1990), pilots' decision making in combat (Secarea, 1990), and paper-mill working processes (Leppanen & Auvinen, 1988). Expert–novice differences in performance, among other factors, were explained by differences in the quality of the subjects' mental models of the device or process (Hegarty, 1988). Across these diverse domains, the common claim is that subjects' mental models affect their acquisition of knowledge and skills, and that the inclusion of modeling support procedures in the instruction may facilitate learning.

The nature of a person's model of a device or process has been described in varied ways. Kieras (1988) suggests that a mental model contains two forms of knowledge: (a) 'how-it-works knowledge', referring to the internal structure and mechanisms of the device; and (b) 'strategic knowledge', about how to use the previous knowledge to perform a task. These two together result in a 'runnable' mental model of the system.

de Kleer and Brown (1983) suggest that constructing a model of a system implies: (a) a representation of the structural configuration of the system, called 'device topology'; (b) a process by which the system's functional configuration is inferred from its structure, called 'envisioning'; and (c) a particular causal model resulting from the envisioning process. At the device topology level, the model consists of several constituents: parts (e.g., energy source, valves, clapper), conduits connecting the parts (e.g., pipes, wires), and 'stuff' flowing through the conduits (e.g., oil, electrons, water).

Finally, mental models of a system can be placed within a qualitative–quantitative continuum (Hegarty, 1988; de Kleer & Brown, 1983). Qualitative models are based on phenomenological descriptions of the components' and whole system behavior, on representing functioning as a sequence of salient events in causal order, and the use of qualitative values (e.g., high, going down). Quantitative models are based mainly on the use of formal representational constructs (e.g., formulas, rules), precise values, and computational procedures.

Summarizing, the following aspects found in the research literature are relevant for our line of research:

1. People use mental models to understand, explain, operate, repair, or design a technological system.
2. Mental models of a system are complex representations. They map the structure of the system (device topology), as well as the functions associated with these structural components, resulting in a runnable mental model of the system.
3. Qualitative modeling precedes quantitative or formal modeling.
4. People's previous naive knowledge and models are central elements in the qualitative modeling process.

5. Experience (repeated activation of the model in many and varied situations) seems to play a central role in the construction and refinement of the model.

However, following this succinct review of previous work a central issue should be noted. The study of the acquisition of generally applicable technology-related knowledge and skills has largely been neglected. Most studies have been done on a user's device model while he/she (usually an adult) is being trained to manipulate that device. In these cases, the learning process is based on the need to achieve specific functional goals; most of the content and skills being taught consist of a defined network of procedures required for operating a device or repairing it. The present study, in contrast, is concerned with the more general area of technological literacy, which we define as the knowledge and skills required for understanding and interacting with the man-made environment (Dyrenfurth, 1991; Johnson, 1989).

Technology involves the use of materials and methods to solve human problems: shelter, health, communication, entertainment, etc. A technologically literate individual understands the more general properties of materials (e.g., plastic, nylon, wood), devices (e.g., thermostat, gear train, gasoline engine), processes (e.g., acid etching, information encoding and transmission), and organizational structures (e.g., hospital, school, soccer team). This knowledge, when integrated, leads to the ability to solve human problems through design of technological solutions. The context for the present study is the typical classroom, where school-age students learn about technological devices and processes as general knowledge and skills, assisted by advanced instructional tools like the Lego-Logo system. Our focus is knowledge about simple control systems such as those found in automatic doors, heating/cooling systems, and household devices. More specifically, we explore mental models of simple control systems held by middle-school students — their conceptions and misconceptions and their use of these models to design solutions for control problems.

CONCEPTUAL MODEL OF THE OPENING/CLOSING SYSTEM

Following Norman (1983), we distinguish among four components regarding the student's model of a technological device or process: (a) the target device or process: (T); (b) the conceptual model of T (C(T)); (c) the student's model of T (S(T)); and (d) the researcher's model of the student model of T (R(S(T))). For example, if we were studying student models of heating/cooling control systems, the T might be a bimetallic thermostat. A C(T) for this thermostat can be found in most textbooks on heating/cooling or on general control systems, and involves, at its core, the tripping of a switch through the differential expansion with heat of two metals that are layered. Through clues obtained in think-aloud protocols, design activities, and the like, the researcher constructs his/her best estimation of the true S(T) of such a device. The researcher model is represented here as R(S(T)), which is usually presented in a form that makes the distance between C(T) and S(T) explicit.

The target T in the study reported here is an opening/closing control system. In general terms, a system is often described in terms of the input it receives (energy, materials, or information), the process it performs, and the output or result it generates. However, if we want to affect in a particular way the processing stage (e.g., we want it to be activated or deactivated after a given time delay, activated only if given conditions are met, or activated in different ways for different situations), we have to add another element to the system, a control component. To clarify this characterization of the kind of systems we are focusing on, we will present a concrete example: a supermarket's automatic door.

The system has a defined goal. The goal in our example can be defined as letting people enter or leave the store, otherwise keeping the door closed. To achieve this goal, the system is built of certain elements which are activated when the opening or closing of the door is needed (e.g., motor, transmission mechanisms). However, those elements are activated according to particular specifications, such as "open the doors when a person is approaching them" or "leave the doors open for x amount of time, then close them." The conditioned activation of the doors is the responsibility of the control component of the system. Given the set of specifications, the control component interprets incoming information (for example, from a sensor situated under a pad in front of the door) to determine that a person is approaching the door. If that is the case, the control will trigger the appropriate action chain leading to the actual opening of the door. This sequence will be repeated every time the control component receives information about someone trying to enter or leave the supermarket.

The C(T) of the opening/closing system can be represented as shown in Figure 1. Two main modules are represented: the control unit (CU) and the operating unit (OU). The OU contains the mechanical devices that perform the actual opening/closing as well as data collection components such as light or pressure sensors. These sensing devices in the OU collect information and transmit it to the CU, where, according to the control specifications, the appropriate signals (instructions) are selected and sent to the mechanical components of the OU. Therefore, the CU contains devices that can store

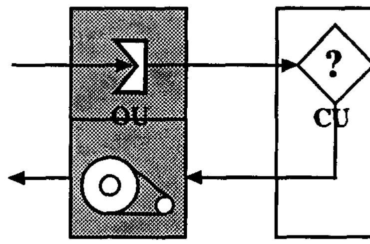

Figure 1. Conceptual model of the controlled system. Abbreviations: CU = control unit; OU = operating unit.

and compare data and generate signals appropriate for activating particular components of the OU.

In this study, the conceptual model of the system served two purposes. First, the conceptual model guided the design of the instructional tasks, described in the Methods section. Second, the conceptual model served as the reference for the analysis of the student representations and Lego-Logo designs and the construction of our understanding (R(S(T))) of the student models (S(T)).

METHOD

Subjects

Nineteen students in a sixth-grade gifted and talented class worked on a series of activities focusing on the analysis and design of opening/closing control mechanisms. The school is a public, intermediate school covering Grades 4 to 6 and located in an ethnically mixed working-class neighborhood. Some of the students are bussed to the school from other neighborhoods, including high socio-economic status ones. The class was selected on the basis of competitive testing and was predominantly white.

Procedure

A series of control mechanism activities were taught by the senior author. The classroom teacher participated, supporting the groups' work and assisting with the class discussion activities. The class met for 12 sessions over a 3-week period. Most sessions lasted 45–50 min; a few lasted 60–70 min. Some exercises and design work were done by the students as homework.

Instructional Materials

The instruction was based on materials developed within the framework of the Educational Testing Service/University of Delaware science project (Gong, Venezky, & Mioduser, 1992), a school reform project that emphasized instruction-based assessment, hands-on science and technology, and an integrated curriculum motivated by environmental and social problems evident in the student's world. For this unit, a series of activities were developed, some of which used a Lego-Logo environment. The Lego-Logo environment, used by the students for designing and building the systems, combines two elements. The first element is the Lego building blocks. Besides the normal Lego blocks, the students used kits which included technical pieces (e.g., gears of different kinds, wheels and axes of various types and sizes, sensors, motors, lights) which allowed them to build working physical models and devices. The second element of the environment is the Logo computer programming language, enhanced by the addition of a particular set of instructions to control (by means of the computer) the Lego model. For example, motors and lights can be activated, and data from the sensors can be collected, using Logo instructions. Complete control procedures for a Lego-device can be defined as Logo procedures. An interface box and a set of wires connect the Lego model to the computer.

The class instruction, shown in Figure 2, proceeded as follows. The initial activity was aimed at developing with the students the model of a control loop through analyses of familiar situations. For example, the first situation consisted simply of tossing and catching a coin several times. Throughout this activity the students were asked to fill in a series of tables, noting the parts of the body involved in the activity, then the senses and their roles, up to the controlling functions and a formulation of the possible control rules.

Once the initial version of the model was formulated, the succeeding sequence of activities focused on its repeated implementation to a series of new situations. First, an analysis task: the students had to select and analyze one example from a set of examples of opening/closing systems from the natural, artificial, and social worlds (e.g., the Venus flytrap, the epiglottis in our throat, an automatic door created by Hero of Alexandria almost 2000 years ago). Next, a design and building task: the students had to design and build a Lego-Logo working model of an automatic door, including the control specifications to be formulated as a Logo program.

Data Collection

The worksheets, drawings, and actual Lego models were the source of the data and conclusions in this paper. The data presented in this paper were collected at three points:

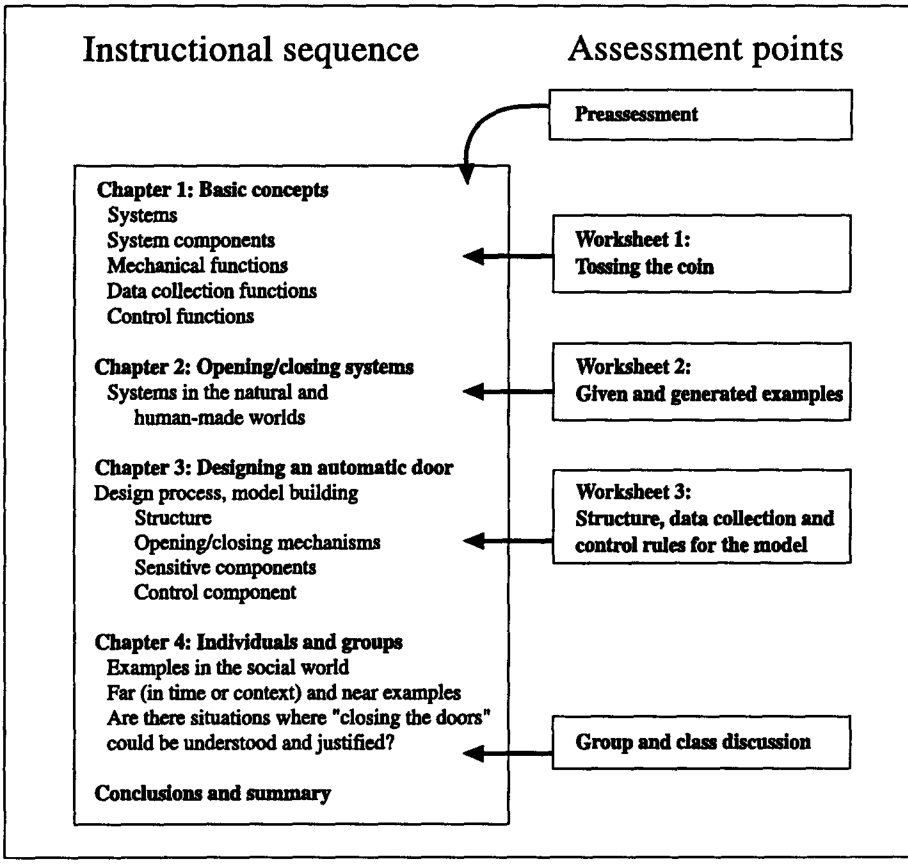

Figure 2. Instructional sequence and assessment points.

1. Prior to instruction (preassessment): the students were asked to describe how an automatic door works, using drawings and written explanations;
2. At the analysis stage: the students were asked to apply a previously developed conceptual model for analyzing varied examples of opening/closing systems;
3. At the design stage of the Lego-Logo model: the students created a design document for their automatic door project. They drew and described in words the projected system. They then detailed the control component: the kind of information collected by sensors and the set of possible decisions or actions that could be made using that information. Finally they formulated the decision-making process in the form of a set of IF . . . THEN rules.

In addition, a series of short interviews were conducted at the time each group finished the building of the model, connected it to the computer interface, and activated the computer program.

RESULTS

Students' Perception of Control and Device Knowledge

Perception of the control process. The first question we addressed relates to the kinds of models the students held about opening/closing mechanisms at different stages of their work.

Using as a reference the conceptual model of the opening/closing system shown in Figure 1, we analyzed the student representations. We classed the representations according to the extent to which the different components of the Figure 1 conceptual model were included by the student. By using this procedure, we obtained a sequence of qualitative models (White & Frederiksen, 1987). The main property characterizing the sequence (Figure 3) was that of increasing differentiation in representing structural and functional aspects of the system: from an undifferentiated general input/output model (Figure 3a), up to the complete causal model (Figure 3d). The sequence consists of four types of models: 'black box', 'reactive', 'switch', and 'control'.

The first type of model is labeled a 'black-box' model of the system. It mainly describes the overall behavior of the system, indicating that in the presence of an input (e.g., someone approaching the door) it produces an output. Structural and functional aspects are ignored, as well as the process by which the output is generated.

Examples of what we classed as black-box representations are:

> You go near it and it opens, you go away from it, it closes.
>
> 1. You walk to the door; 2. It opens; 3. You walk in.

In the second type of model, labeled 'reactive', sensing functions (and sensing devices) are now differentiated and explicitly mentioned, and the activated elements of the system are described in some detail. With this model, the system is perceived primarily as a 'sensing–acting' device.

Examples of the student descriptions are:

> You step on a particular place which triggers a sensor and door opens.
>
> [about the Venus Flytrap plant] 1. A fly lands on the plant; 2. The three sensitive hairs are triggered; 3. The toothed edges close and the leaves close together; 4. The plant eats the fly.

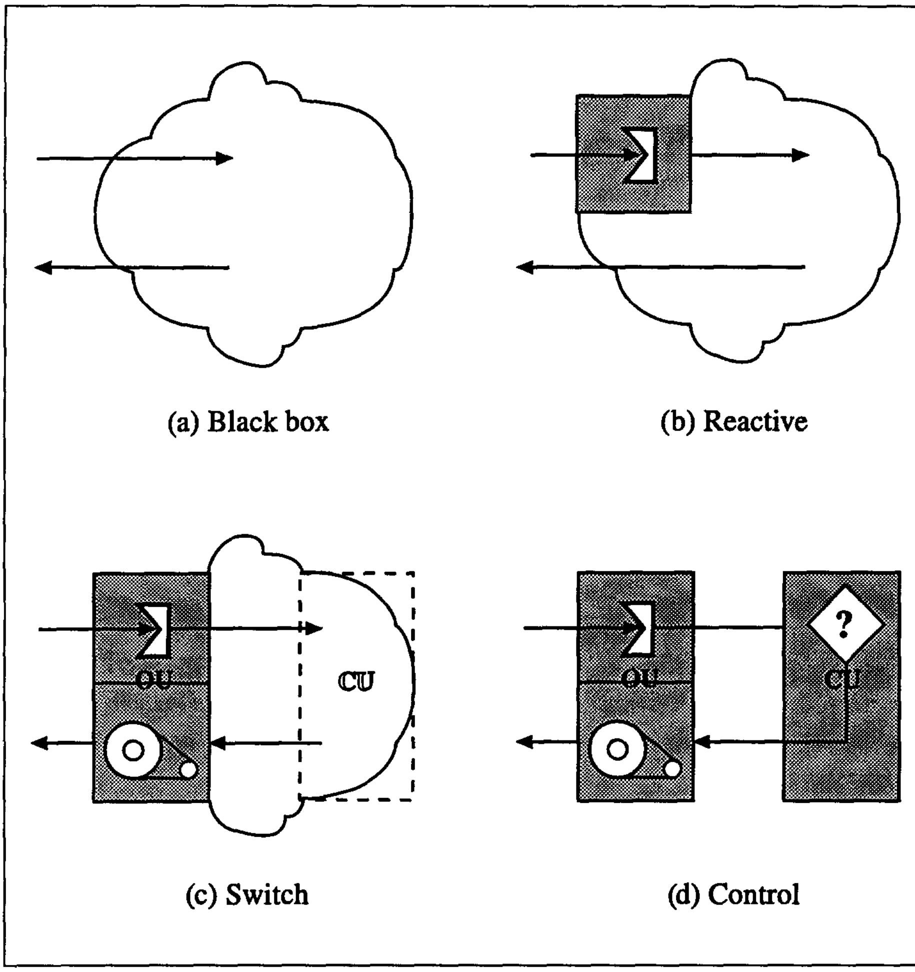

Figure 3. The sequence of qualitative models of the controlled system.

> There is a weight sensor under the mat, when weight is put there it connects the circuit and a motor uses a rack and pinion to open the door.

In the third model type, labeled 'switch', a separate commands-delivering function appears, reflecting student awareness of the need for a controlling module which instructs the activated elements on a course of action. However, the nature of the controlling function remains undefined and there is no reference in the representation to controlling rules or procedures.

Examples of student descriptions are:

> [about the eyelid] The Brain controls when to open and close, it sends a message to the eyes . . . When the eye sees something coming it sends a message to the brain. The brain

> sends a message to the eyelid, telling it to close, it closes then reopens a few seconds later.
>
> 1. You walk up to the door; 2. The movement sensor sees you; 3. The sensor takes the information to a microbug; 4. The bug opens the door.

The fourth model is the complete causal model (already shown in Figure 1). Control specifications are included, and even represented in some formal way (e.g., control algorithm, productions). The explicit definition of control specifications implies also the ability to refer to causal relationships in the system's functioning and explain changes in time. This was labeled the 'control' model. Consider the following example:

> We are planning to build a trapdoor, that moves from side to side. The door will run on tracks . . . When someone (or something) steps on a part near the door, the door will move over, or if someone breaks the light sensor, the door will open . . . The door can move forward or backward, depending on where the sensor is broken. The door can be opened from below, when someone turns the wheel from the inside . . . [about the rules governing the doors operation:] IF someone breaks the sensor then the motor will turn the gear, and the door will open. IF someone turns the wheel then turn the gear to open the door. IF something does not break the full sensor, then do not open. IF something goes through both sensors within 5 s, then do not open . . .

This example (in the students' planning sheet accompanied by a drawing of the trapdoor) shows a comprehensive concern with the structural composition of the system being built, the action chain comprising its functioning, and the rules (to be programmed on the computer) defining what is going to be activated in what conditions.

The frequency distribution of the representations classed by the four types of models is shown in Table 1. About half of the total number of representations generated by the students at the different stages were of the reactive (sensing/acting) type. About a quarter were black-box-type representations, and only 10 (17.5%) referred explicitly to control functions or specifications. At the preassessment stage, most students (52.6%) described the automatic door as a reactive system. No student included an explicit description of the control module in the system's representation. At the analysis stage, once again the most frequent kind of model was the

Table 1. Frequency Distribution of the Representation Types at Three Points During the Instruction

Mode	Preassessment	Analysis	Design	Total
Black box	5 (26.3%)	2 (10.5%)	7 (36.8%)	14 (24.5%)
Reactive	10 (52.6%)	10 (52.6%)	7 (36.8%)	27 (47.3%)
Switch	2 (10.5%)	2 (10.5%)	2 (10.5%)	6 (10.5%)
Control	0 (0.0%)	1 (5.2%)	3 (15.7%)	4 (7.0%)
No relevant representation	2 (10.5%)	4 (21.0%)	0 (0.0%)	6 (10.5%)
n	19	19	19	57

reactive type. Although fewer representations were of the black box type, about a fifth of the students did not generate a relevant representation at all. At the design stage, most representations were of the black box and reactive types (36.8% each). Representations referring explicitly to controlling functions (switch and control models) increased slightly between the preassessment and design stages (from 10.5 to 26.2%).

Device knowledge. The second question we addressed relates to the students' knowledge of structural and functional components of the system at the different stages of the learning sequence. We analyzed the way this related to the two main components of the system, namely, the OU and the CU. The following is the classification scheme we have adopted.

Structural configuration of the OU. We divided the representations into three categories, labeled 'undefined', 'collection', and 'coherent set'. The first category, undefined, comprises those representations ignoring any structural aspect, or indicating that the student has only a vague idea of what the structure of the system consists of. The second category reflected the conception of the system's structure as a collection of components, without clearly indicating how these are organized and interrelated.

A representation of the coherent set category indicates that the student perceived the system as a coherent and organized structure. These descriptions were reasonably complete in terms of the major components and their structural relations, even if not always accurate. For example, the following comment complemented a detailed drawing for the design of a drawbridge:

> The purpose of the castle is trade and defense. In order to defend it, a drawbridge has to be made. At peace time, the weights (a), help to keep the bridge (b) open. If there was a threat of war, the wheel (e) that was attached to the chain at the wall (c), could be rotated in order to raise the bridge. The moat (d) would have to be crossed in order to reach the town road (f).

Configuration of the CU. In a similar way, we defined three categories for classifying the student representation of the control component: 'undefined', 'collection', and 'control'. As with the OU, the representations of the undefined category do not include any explicit reference to control functions or specifications. They focus mainly on the observable behavior of the system, mostly in general terms (e.g., "The info that the sensor is collecting: when a car or person is approaching trying to enter the area. The automatic door can open, close, and move up and down").

Representations of the collection category of the CU reflect some awareness of specific control features, but these are depicted as a collection of individual functions. In addition, no explicit mention is made about control specifications, rules, or the like, which stand behind and cause the controlling functions (e.g., about the touch-sensitive plant: "1. Fly touches two hairs; 2. The sensors make the Venus flytrap close; 3. The Venus flytrap presses hard and crushes the fly; 4. It is finished with the fly").

The control category of representations reflected the ability to envision the whole functional map of the system, to refer to detailed causal chains in its functioning, and to explicitly describe control specifications or procedures (e.g., about the design of a drawbridge: "The information that the sensor gathers corresponds to a change in weight. When the drawbridge is down a person(s) can walk over it. His weight counter reacts to the weight at the opposite side. After the person reaches the side with the weight, the drawbridge closes. [IF] Someone is proceeding towards the bridge [THEN] Turn the wheel that would lower the bridge so the person may enter. [IF] a heavy load is coming [THEN] lower the bridge and bolt it down, so the weight of the object won't counteract with the weight on the bottom of the bridge").

Table 2 shows the distributions of representations for the OU and CU. The distribution at the preassessment and analysis stages for both aspects was identical. At the preassessment stage, the majority of the students (63.1%) generated a vague representation of the systems, their nature and features. At the analysis stage of instruction, a considerable number of students (31.5%) were able to represent the OU as a coherent structure, and the CU by the set of decisions and rules involved in the behavior of the system.

It was at the design stage where differences between the representations of the OU and CU appeared. The majority of representations (84.3%) showed a fairly complete structural description of the system to be built. On the other hand, only a few (15.1%) included a similar level of description of the CU at

Table 2. Frequency Distribution of the Representation Types for the Operating and Control Units at Three Points During the Instruction

Category	Preassessment	Analysis	Design	Total
Operating Unit				
Undefined	12 (63.1%)	5 (26.3%)	3 (15.7%)	20 (35.1%)
Collection	5 (26.3%)	4 (21.1%)	0 (0.0%)	9 (15.8%)
Coherent set	0 (0.0%)	6 (31.5%)	16 (84.3%)	22 (38.6%)
No relevant representation	2 (10.5%)	4 (21.1%)	0 (0.0%)	6 (10.5%)
n	19	19	19	57
Control Unit				
Undefined	12 (63.1%)	5 (26.3%)	8 (42.1%)	25 (43.8%)
Collection	5 (26.3%)	4 (21.1%)	8 (42.1%)	17 (29.8%)
Causal	0 (0.0%)	6 (31.5%)	3 (15.7%)	9 (15.8%)
No relevant representation	2 (10.5%)	4 (21.1%)	0 (0.0%)	6 (10.5%)
n	19	19	19	57

this stage. Most representations of the control features at this stage were of the undefined and collection categories.

Finally, we looked for significant differences among the representations at the different stages for the OU and CU. The means appear in Table 3.

In comparing the student representations of structural and control features, significant differences were found between the preassessment and the design stages both for the OU, $t(18) = 8.61, p < .001$, and CU, $t(18) = 3.01, p < .001$). While there were no differences between the OU and CU at the preassessment stage, significant differences between these two were found at the design stage, $t(18) = 5.29, p = .001$). Significant differences were also found between the overall mean of the OU and CU representations, $t(18) = 3.478, p = .001$).

An ANOVA test showed significant main effect of the instructional stage (namely, preassessment, analysis, and design stages) for the operating ($F = 20.06, p < .001$) and control ($F = 3.29, p < .05$) levels. A Scheffé F test showed significant differences between the preassessment and design stages for the structural issues ($F = 19.14, p < .05$), but not for the control-related issues.

Focal Observations

Complementing the previous analysis, in this section we present several focal issues that characterized the students' missing and missed conceptions of structural and control features of the opening/closing systems.

Misallocation of control functions. One of the most frequent misconceptions was the allocation of control functions into different components within the system. A salient example reflecting this misallocation was the 'sensor-to-motor model of information flow'. In this model, the sensors communicate directly with the motors, and decisions about the door's status occur somehow from this interaction. The model appeared in the student

Table 3. Overall Means for the Operating and Control Units at Three Points During the Instruction

Module	Preassessment	Analysis	Design	Total
Operating Unit				
M	1.15	1.63	2.68	1.82
SD	0.60	1.16	0.74	1.00
Control Unit				
M	1.15	1.63	1.73	1.50
SD	0.60	1.16	0.73	0.88
Total				
M	1.15	1.63	2.21	1.66
SD	0.57	1.15	0.63	0.59

representations under different wordings and formulations. Sometimes the sensor was the controller (e.g., "sensor to open the two gates", "when object comes by, the sensor senses the object and lets it pass by lifting both bridges" or "the sensor should collect light. If it does not collect light it should activate a switch opening the door." On other occasions, control functions are vested in the motor (e.g., "When a car crosses the path of light a shadow is sensed determining the presence of a car. This sensor sends the information to the motor", "the different shadow the approaching vehicle casts helps the motor determine whether to open the gate to this type of car or vehicle." This model was strongly present in the way the students reasoned about the functioning of the opening/closing systems, even after they had successfully completed the building of their Lego-Logo models.

Who closes the open loop? An interesting aspect of some student conceptions of an artificial opening/closing mechanism was that it consists of a human–machine or user–device complex system. Clear examples of this are the student examples shown in Figure 4. While the opening/closing mechanical parts are part of the artifact, the decision-making and activating components are supplied by the user.

This human–machine view appeared again in the building stage of the Lego-Logo models. Most models produced by the students at this stage included a piece (e.g., handle, wheel) allowing hand operation. (Keep in mind that the task was to build a motorized and computer-operated automatic door.) To some extent, it is reasonable to include hand-operated pieces in a model to test its functioning before the attachment of motors and their connection to the interface box. However, in some cases we found that the human–machine-system view guided not only the design of the model's structure, but more significantly, the control rules. The following is an example of a double set of rules for controlling the functioning of a trap door. The rules contemplate the possibility that two alternative systems, a self activated one and a human–machine one, are being controlled.

Rule a "IF someone breaks the sensor THEN the motor will turn the gear, and the door will open."

Rule b "IF someone turns the wheel, then turn the gear and open the door."

We have observed that the computer-based control is the weakest and least understood component in the students' perceptions of the structure and function of the Lego-Logo models. We believe that additional experience in building computer-controlled systems would gradually contribute to the students' understanding of the nature of the control module in the system, but this hypothesis obviously deserves more systematic observation.

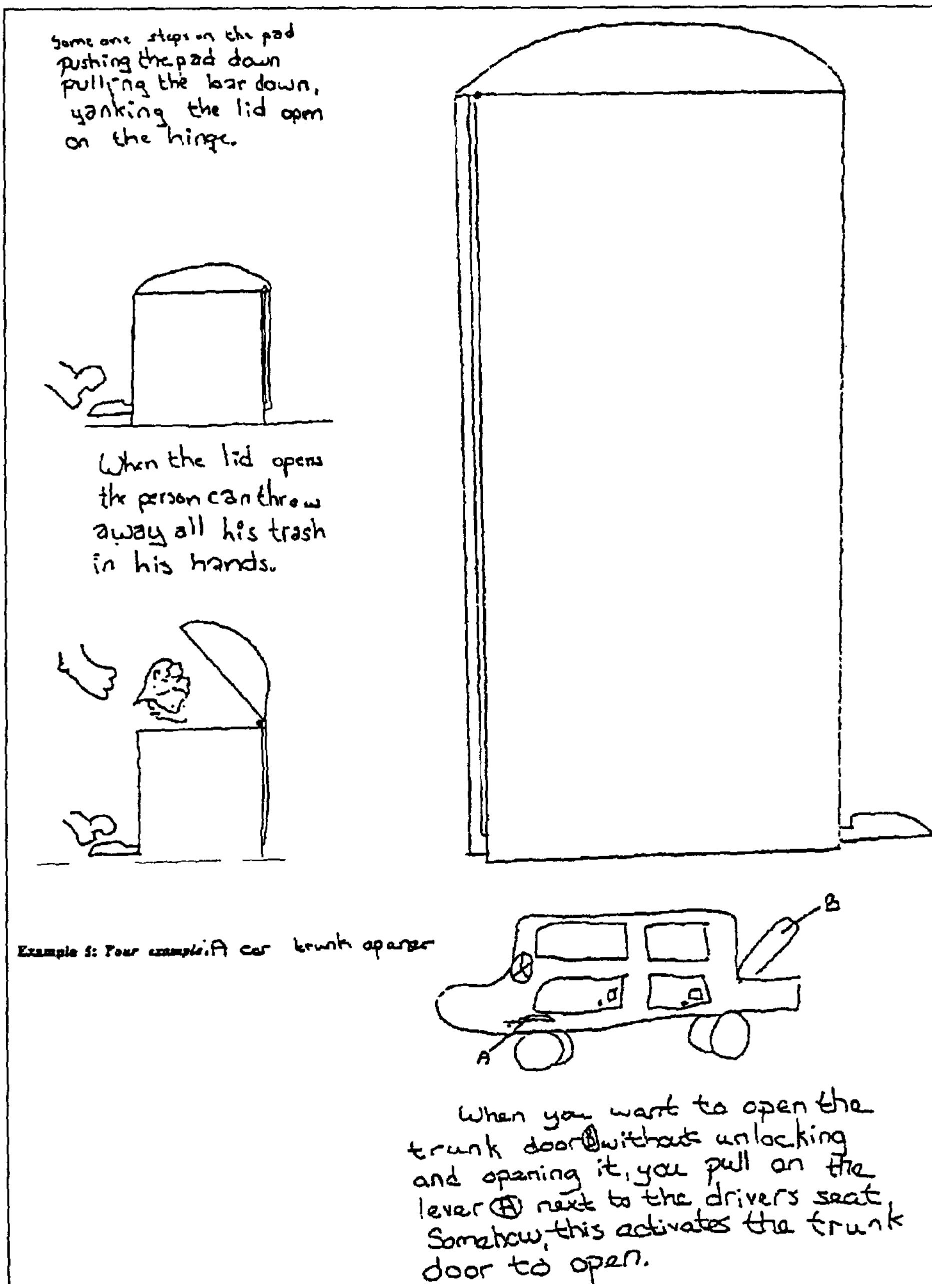

Figure 4. Examples of human–machine or user–device complex systems.

'Stuff' and information. In their description of models of physical systems, de Kleer and Brown (1983) referred to the 'stuff' contained in conduits, mediating the interactions between the model's components. The stuff could be electricity, water, or oil (Williams et al., 1983). The nature of the stuff and the way it conveys information among the system's components was one of the significant omissions in the students' representations, whether they referred to natural or artificial phenomena, or to the Lego-Logo model design.

The few mentions made by the students were about electrical impulses (e.g., for the Venus flytrap or the mouth examples), nerve impulses (e.g., for the eye example), 'messages' (e.g., for the automatic door example), or an undefined 'it'. Equally confused in most cases were the descriptions about the senders and recipients of the information or stuff conveying it. For example, "A sensitive feeler is put in front of a door. When someone comes it transfer[s] it to the doors" [from the preassessment]; ". . . sends message to trap that insect is there . . . " [Venus flytrap]; ". . . the brain patterns that signal the jaw to open" [newborn baby].

Sensing and sensors. For the types of systems included in this study, the transition among states (e.g., doors closed to doors opened) is a function of the information collected by a sensor. The sensor's main function in this case was to inform the control component whether the conditions to generate a state change were met or not. In general terms, the students were highly knowledgeable of sensing devices and their functions as early as the preassessment stage. The most frequently mentioned component of the automatic door system in the preassessment stage was the sensor, which was included by about 66% of the students. This is an interesting figure, considering that this reflects the students' knowledge prior to the instruction; it contrasts with their omission of almost all of the other structural components of the system.

A close analysis of the students' representations reveals misconceptions about the nature of the sensors and the information collected by them. In some cases, instead of perceiving the sensor as being affected by changes occurring in the surroundings (a light beam being broken or the weight of an insect), an active role was attributed to it: "a light sensor hits you".

The nature of the information detected by the sensor varied also. For example: "There is a heat sensor on top of the door, and when something alive comes near it, the door opens"; "The movement sensor sees you."

Considerable difficulties in analyzing sensing functions occurred for an example of an automatic door designed by Hero 2,000 years ago. The opening/closing function relies on differences of pressure created in a container by fire burning in the altar, forcing water to flow to a bucket that in turn drops (because of its weight), opening the doors. No particular component could be easily identified as the sensor in the system; thus, the few students who chose to analyze this example supplied interesting explanations: "The fire was the sensor, when it burned the door opened. When it died down, the door closed"; "Heat and air pressure [for sensing] . . . When the fire is out it 'senses' all it [heat and air pressure] to be pulled back"; "The water in the hollow sphere [is the sensing component]."

The complete model. A few representations at the design stage showed a fairly complete perception of the required structural and control configuration of the opening/closing system. One example is shown in Figures 5 and 6. An essential aspect of the system's functioning was that information was being detected, transmitted, evaluated, and used to generate outcomes. The student used a variety of terms and phrases to relate to this issue (e.g., "the car door knows the car is there", "[the light] will travel to the sensor", "a message is sent to the computer", "the message runs up the cable"). As well, the whole information flow was described in detail, including alternative situations at the data detection stage (e.g., one light reaches a sensor, both lights do that, both light beams are blocked, thus, not reaching any sensor) as well at the output generation stage (e.g., the activation or deactivation of the motors according to the control rules).

The control specifications for the student's automatic door appear in her design worksheet in four different ways, as shown in Figures 5 and 6: As comments on the drawings, as a prose description of the door functioning, as IF . . . THEN rules, and as a schematic representation of the 'code' or possible states of the lights and the corresponding outcomes. Further examples of student designs are shown in Figure 7.

DISCUSSION

Control mechanisms are part of almost every object and device in our modern, artificial environment. One can also identify countless manifestations of them in the living environment, including within our own physiological and psychological functioning. Control concepts and explanatory frameworks are being used by people in many diverse disciplines as explanatory, predictive, and design aids. Contrasting with this (apparently) massive presence of control examples in the environment and in professional usage, the preassessment results showed that students had very poor knowledge and understanding prior to instruction. It seems that control system-related knowledge and skills are not part of the students' cultural

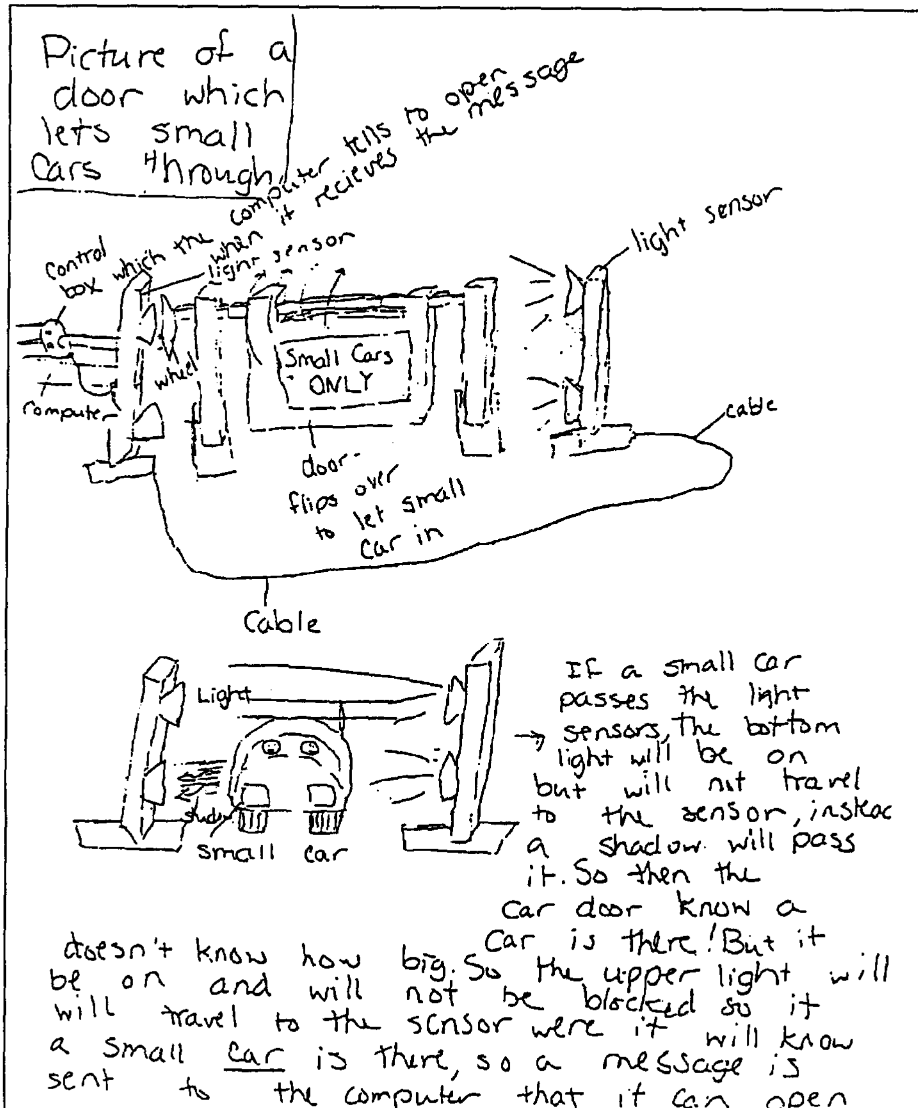

Figure 5. Details of a student's plan of the control specifications for an automatic door.

baggage, being acquired neither by interaction with the control-rich environment, nor through their current formal schooling experiences.

A closer look at the student representations at the different stages helped us to unveil key issues which could be the source of their particular difficulties in perceiving control.

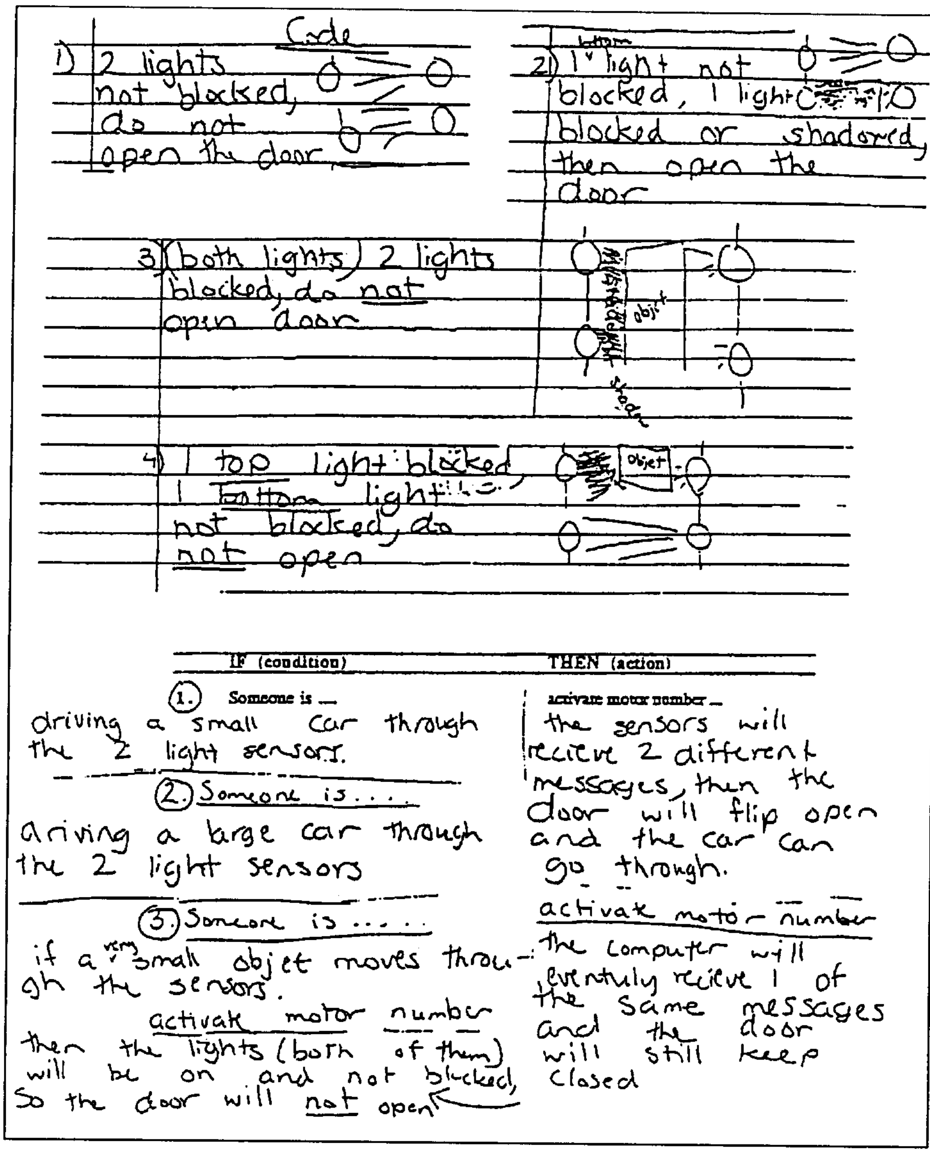

Figure 6. Details of a student's plan of the control specifications for an automatic door.

Device Knowledge

Device knowledge has been found to be an essential characteristic that differentiates expert from novice troubleshooters (Lajoie & Lesgold, 1989), as well as expert from novice problem solvers (Larkin, 1983).

In general, we found that students lacked accurate structural and functional knowledge as well as the overall ability to envision appropriate

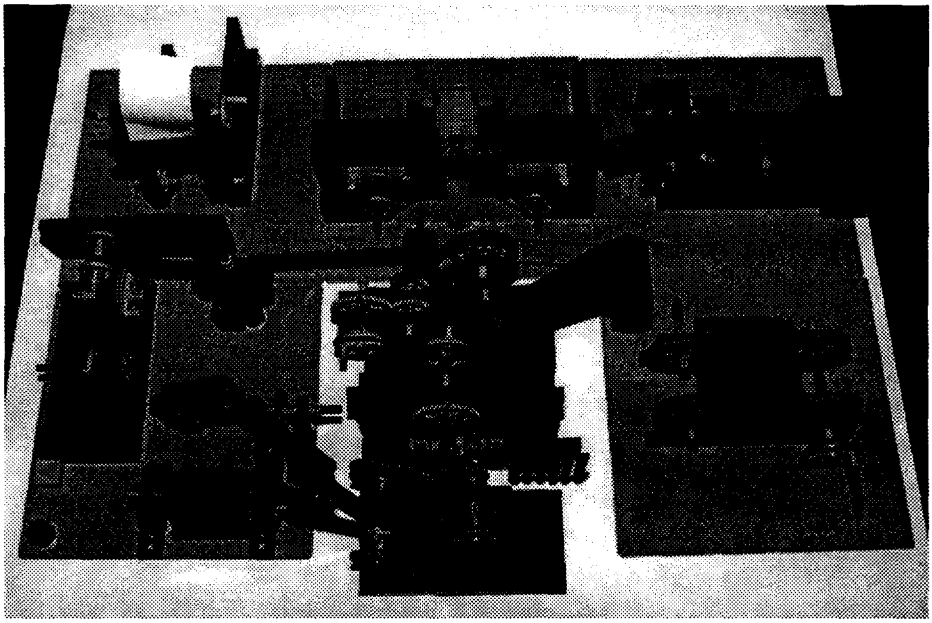

Figure 7. Examples of opening/closing devices designed by students.

runnable models of a system. For example, they lacked accurate knowledge about many common components of present-day mechanical devices and technological systems: switches, motors, levers, etc. Sometimes, this limitation was reflected in faulty understanding about how some device (e.g., a push-button switch) operates; at other times, it was reflected in an inability to define how the behavior of an activated element in a system (e.g., a transmission piece) affects the behavior of the total system.

A common issue was that of missing key elements in the student representations at given stages. For example, half of the students did not include any mention of structural components at the preassessment stage (gradually, all students were able to generate a fairly complete structural description at the design stage). Furthermore, most students did not relate to stuff conveying the information within the system at any stage. Only a few related explicitly to the functional meaning of the transmitted information while analyzing an example (e.g., the mouth) or describing their design of the automatic door.

Another common issue was that of misconceptions about the components' nature and functioning. One clear example was the misallocation of sensing functions (e.g., the fire in Hero's door mechanism was assumed to be the sensor by the mere reason that it was viewed as the trigger for the opening/closing process). The sensor-as-trigger model was the key property by which the fire in the altar and the optical sensor in the elevator's door were perceived by students as members of the same set.

We believe that accurate device knowledge will allow a focus on higher levels of behavior in analyzing or designing systems, just as automated lower-level functions allow attention and working memory to be allocated to higher-level processing in problem solving (Anderson, 1981). However, most students lack this device knowledge, and our 12-week intervention had uneven results in enabling these students to apply such knowledge to a fairly simple example.

Perception of Control

Previous studies have found a tendency for younger students to assign agency (e.g., conscious decision to act, to react, to initiate a process) and animacy (e.g., perception of physical causality in terms of psychological intentionality) to inanimate devices or their components, relating to control in terms of transactions among these agents (Ackermann, 1991). As they develop, children tend to use more and more mechanical-causal explanations. However, by high-school age, students tend to overgeneralize the need for a central control mechanism assuming, for example, that all regular, inanimate behavior (e.g., traffic jams) requires central control or cause (Resnick, 1991, 1994).

In our study, the distinctive ability of the students to perceive the structural and the control features of a system appeared clearly. For example, at the design stage (after dealing both with analysis and design tasks) almost 85% of the students perceived a system's structure as a coherent set of subsystems and components, while only about 15% recognized its complete set of causal chains control features. It was clear that identifying and formally defining the control features of the system (the 'unseen' unit as opposed to the visible OU) presented serious difficulties to the students. Control was perceived mostly in behavioral or phenomenal terms, as reflected in the descriptions of 'what' the system does do more than 'how and why' it behaves that way.

Communication and Control

Controlled systems require communication of information from one device to another for proper functioning. For example, a heat sensor must send information to a threshold tester, a weight detector must send information to the mechanism that controls the opening and closing of an automatic door, and light intensity detectors in the eye send information to muscles that adjust the size of the pupil. Most students in our study showed faulty or incomplete knowledge on how components communicated with each other and how resultant actions synchronized to achieve a defined goal.

de Kleer and Brown (1983) suggested that one main source of inadequacy of a model (e.g., ambiguity, inaccuracy) are the implicit assumptions (about the nature or functioning of a component or components) introduced by the subject in the model. One level of implicit assumptions in our study refers to the kind of information collected by the sensors. For example, some students described the sensing device in an automatic door as a heat sensor reacting when 'something alive' is approaching the door. Trying to maintain consistency with this implicit assumption, we presume that the student will have some difficulties in predicting what will happen when only a shopping cart approaches the door, after being pushed from a reasonable distance. Another level of erroneous implicit assumptions relates to the flow of information within the system. For example, using the sensor-to-motor communication model (as opposed to the complete sensor-control-motor communication model) students allocated decision-making functions either to the sensors or to the motors.

IMPLICATIONS FOR FUTURE WORK

Some preliminary conclusions can be drawn related to the instruction. The first is about the facilitating role of the model building kits, in this case the Lego-Logo system. These kits constitute an accessible environment for the practical exploration of ideas and solutions. Furthermore, they allow the students to explore concretely aspects of control systems still poorly understood by them at the conceptual level. For example, most students showed a poor or incomplete perception of the functional configuration of the systems when they entered the design stage. Nevertheless, they gradually completed their models of the automatic door, overcoming in the process inconsistencies and erroneous implicit assumptions that characterized their earlier written and drawn representations. Based on these observations, we hypothesize that the model building process both reflected and affected the gradual consolidation of the student conceptions of the controlled systems.

White and Frederiksen (1988) proposed two hypotheses related to the link between instruction and people's mental models of physical mechanisms. The first is that instruction has to supply models that represent the system's behavior from different perspectives, such as the macroscopic and microscopic levels. The second hypothesis is that students have to be introduced to simplified models in early stages, and to gradually refine these in successive stages. Our instructional approach incorporated the idea of multiple and coordinated perspectives. However, instead of supplying a simplified model to be refined at later stages, we presented, at the very beginning, what may be called a 'functional skeleton' of the system. Our hypothesis is that the basic model is being upgraded (rather than replaced) at successive stages, mainly as a result of its repeated implementation either for understanding, describing, explaining, or designing different kinds of new examples of the system in question. Each component of the functional skeleton is being utilized in different ways for each new example (e.g., the Venus flytrap sensitive hairs, sight and touch senses, thermostat, the Lego optosensor). This allows the students to expand their repertoire of known manifestations of a given function, and the different ways it interacts with components and contributes to the overall functioning of the system. We assume this repeated implementation is essential for the evolution and crystallization of the conceptual model, particularly for design and building purposes.

We found the information-related issues to be the most difficult aspects of the system to be modeled. Issues including what kind of information is detected by the sensing devices, how it is transmitted, who is in charge of interpreting it and making decisions (and how) were at the root of many misconceptions or omissions in the student models. An immediate implication for the instruction is the need to raise this aspect of the system functioning to the explicit level and to focus part of the repeated implementation experiences on it. For example, computer-based tools (e.g., simulative environments) could supply the context for a more mindful exploration of how information flows among the system components.

A few words about representational means. Formal notational systems (e.g., schematic diagrams, block diagrams) are commonly used for both the analysis and design of technological systems. These notations became the language for accurately dealing (e.g., thinking of, discussing, predicting functioning) with a system's features at the representational level. Yet, little attention has been given to the development of instructional sequences that would lead students to acquire these representational skills. The study has shown that students do not easily acquire the ability to use formal representations of the systems. Part of the problem in acquiring better understanding of technological systems rests with the encapsulation of most modern mechanisms. The acquisition of appropriate representational means, both for seen and unseen features of the systems, may play a central role in the students' ability to analyze, reflect on, and design controlled systems.

This study served to identify general properties of the student models as well as the virtues and weaknesses of our instructional assumptions. We have also identified potential cognitive obstacles that may appear with greater intensity when more complex concepts appear. To mention only one example, we intend, in future studies, to focus on the student models of feedback or closed-loop systems. It is obvious that information collection, transmission, and processing are key issues in those kinds of system and that the basic problems observed in the students' performance for simpler systems could be greatly amplified there.

Finally, we had the opportunity to refine our initial set of research questions. Again, to mention only one example, we have realized that the student's awareness of the need and presence of the control function, and even the identification of the control component, does not automatically mean equal capability to understand, describe, and formulate the control laws as part of the system model. At the design stage, most students phrased the control laws in phenomenal or behavioral terms (what is observed), rather than in functional terms (how the system actually processes the information and produces outputs on acting components). We expect our research questions on this and other aspects of the student's understanding of feedback systems to benefit from our observations in this first study.

CODA

A student's pragmatic conclusion, due to her renewed view of a well-known and obvious mechanism:

> When something comes close they shut because it [the eye] protects itself.The brain tells the eye shut through nerves.There would be a lot of eyeless people if it didn't shut.

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