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Young children's learning of water physics by constructing working systems

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Abstract The present study explored young 5–6-year old children's design-based learning of science through building working physical systems and examined their evolving conceptions of water flow. Fifteen children in an experimental group individually built water-pipe systems during four sessions that included end-of-session interviews. In addition, they were interviewed with a pretest and posttest. The interviews consisted of near and far transfer tasks testing for the children's understanding of three physical rules of water flow and their combined application. To control for testing, maturation and familiarity with the interviewer, a control group was interviewed as well. It was found that through building, the experimental group children's understanding of the related physical rules grew substantially, showing a strong effect size. Moreover, the builders demonstrated budding abilities in coordinating two physical rules. Three distinct conceptual models regarding water flow were found: water can flow along a path disregarding height considerations; water can only flow downwards; and a coordinated view combining gravitational considerations and equilibration within connected vessels. The children's new understandings were found to be local, fragile and bound by developmental constraints. The control group but not the experimental group learned one of the physical rules in the far transfer tasks. The merits and limits of learning science through designing and constructing working physical devices are discussed.

Keywords Learning through design · Concept formation · Science learning · Constructionism · Preschool education

> … it would seem that progress made in the sphere of machines preceded progress in explanation of natural events… It is in making things and in seeing them made that the child will learn the resistance of external objects and the necessity of mechanical processes. Thus the understanding of machines would seem to be the factor which brought about the mechanization of natural causality… (Piaget 1956, pp. 233–234).

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Introduction

This study has set as its main goal the identification of young children's learning of science through building dynamic working systems. The proposal entertained in this study is that through constructing with well-designed learning environments young children come to abstract the physical rules underlying their constructions; this learning is limited by cognitive-developmental constraints but partially expands beyond these bounds as intellectual growth involves not only the learning of scientific concepts, but touches upon structural aspects of reasoning.

The author's view is consistent with a constructionist philosophy of education (Papert 1980/1993), which argues that creating personally meaningful objects is a major source of personal growth. In the process, the ongoing interactions with the system under construction feed the interplay between ideas and their realization, leading to deep learning. Building physical systems reifies the builder's causal models, externalizing such models, as they stand apart for inspection, reflection, revision and further refinement.

Water-flow dynamics were selected because of research considerations: (a) *Novelty*: The system was equally unfamiliar to all the children, to circumvent the effect of prior knowledge; (b) *Room for growth*: children hold robust and often non-scientific ideas regarding the rules governing flow, so that the study could capture a number of learning episodes; and in service of educational design: (c) *Observable mechanisms and phenomena*: The system is transparent and its mechanics are viewable; (d) *Manipulability*: The system provides the builder with numerous degrees of freedom in constructing the structure and in its operation; (e) *Joyful engagement*: water play captivates young children; this feature is important in itself and ensured the children's willingness to participate in several building sessions. The current study approaches preschool children's learning and its transfer to new contexts as well as changes in complexity and consistency in reasoning, accompanying the construction of working water systems.

Background

Young children's time at preschool (and home) is heavily marked by activities involving construction with concrete materials from the earliest conception of preschool education (Froebel 1897; Montessori 1964) to our current times (Brosterman 1997; Hughes 1999). When they are free to choose their activities, they most commonly select such pursuits (Rubin et al. 1978). Building and exploring physical objects plays an important role in school settings for younger ages, geared towards supporting children's investigation of abstract concepts (e.g. Brosterman 1997). However, in practice, little is children's spontaneous free-form construction reflected upon and supported for learning science concepts. Moreover, little research has been conducted into how construction activities may be related to science learning (Hughes 1999, p. 171). This study contributes towards understanding such learning and its support in educational settings.

In the field of science education, it has been found that younger and even older children orient towards producing desired products within experimentation settings. Rather than search for relations among causes and effects, they manipulate variables to obtain a favoured outcome (Kuhn et al. 1992, 1995; Njoo and De Jong 1993; Schauble 1990; Tschirgi 1980; White 1993; Zimmerman and Glaser 2001). This orientation has been named an 'engineering' model of experimentation, in contrast to the less biased and wider ranging knowledge-seeking 'scientific' model of experimentation. Moreover, it was found that shifting from an engineering problem to a scientific problem, rather than vice versa, was more conducive to learning the underlying causal relations (Schauble et al. 1991). Thus it would seem that a developmentally appropriate progression should start from designing for desired outcomes and gradually shift to scientific experimentation.

In recent years, science and technology curricula have joined forces, as the human-made world, systems and design (three components of technology, distinguishing between artifacts, inter-connected artifacts and the processes of goal-setting, exploring, planning, creating and evaluating new artifacts) have been advanced as themes in the standards of science education (e.g. AAAS 1993; NRC 1996). In several countries, such as the UK (Department for Education and Employment 2000) and Israel (e.g. Israel Ministry of Education 1995), combining science and design in classrooms has established technology as an integral subject of study for all students from preschool to high school. Potential cross-fertilization between activities and knowledge marking these two domains is explored in the current study.

In terms of the content learned, this study focuses on children's understanding of water flow. While flow pervades our everyday life-in kitchens, rivers and traffic-very few investigations have been conducted into how people understand this topic.

Braiding the three strands—young children's gravitation towards construction, the value of construction for learning science and an increasingly widespread emphasis on combining the learning of technology with that of science—provides the rationale for this investigation into young children's learning through building. More specifically, the study wishes to augment our understanding of ways to enable young learners in developing an understanding of scientific phenomena through design-based learning environments: Can children's natural predilection for construction be harnessed towards learning of science? If so, what forms of growth does this learning present?

Literature review

In the following review, four topics are examined: current approaches to integrating design and science learning, children's learning through constructing systems, their inference of rules, and how they understand the physics of water flow.

Design and the science curriculum

A number of curricular approaches in both technology and science education have advanced the construction of technological devices as a central activity, encompassing the design, construction and exploration of artefacts and the learning of the related ideas in science.

From the domain of design and technology education, Sidawi (2009) reviews the teaching of science through designing technology. A common tenet is described: that designing technology by solving open-ended problems presents students with a context to apply science concepts and results in a deeper understanding of these concepts. A variety of approaches were developed to support students' learning of science through designing and making technology: "science-through-technology curricula", "learning in technology-centered classrooms", "learning science by designing technology" and "problem solving through technology" (Rowell et al. 1999). In addition programs centering on design while integrating learning with mathematics and science have been reported as successfully supporting learning (e.g. Norton 2007), as have problem-based learning approaches that integrate a wider range of STEM knowledge (Lou et al. 2010).

In the domain of science education, a number of approaches were developed as well. Design-Based Science high-school curricular units involve designing artefacts as a way to learning transferable science knowledge and problem-solving skills; establishing significant learning gains of the related content and skills (Fortus et al. 2005). Design-based learning combines engineering design and science inquiry, and demonstrated high-school students' learning of chemistry concepts through designing heating and cooling systems (Apedoe et al. 2008). In Learning by Design™ activities, middle-school students are presented with conceptually rich challenges; related research demonstrates advantages in learning of physics with respect to comparison classes (Kolodner et al. 2003). Design for Science involves analyzing, designing and constructing technological artifacts as a meaningful framework and was seen to promote scientific reasoning skills among urban low-income middle school students more than learning with both traditional and inquiry-based curricula (Silk et al. 2009). Performance project-based science curriculum uses design tasks to support students' need for learning science and subsequent learning of biology among middle school students (Kanter 2009). Elementary students were studied during two months of activities involving rollers, in which they learned the relevant causal relations (Liu 2000).

No research was found targeting *preschool* children's learning of science through building in the design and technology education or in the science education community. The current research extends the research to younger ages.

Learning science through building artefacts

The creation of objects that work involves one of the fundamental ways of learning: the cycling between constructive action upon tangible objects and reflection upon its results. More recent learning theories that stem from Vygotsky's (1978) work include an emphasis on the role of collaboration with peers and a teacher's guidance in the learning process, to enable learning beyond the actual developmental level of a child (there, pp. 84–91; Bransford et al. 1999). Vygotsky also stresses that mastering artefacts or culturally transmitted tools is central and unique to human development (there, pp. 19–30). In this study, young children work independently with such tools, by creating working objects. It examines the following proposal: well-designed cultural tools may support child's learning, mediating and scaffolding such processes analogously to the social mediation that supports a children's development into the zone of proximal development (Salomon 1993).

Building working systems is a form of problem solving, transforming a given situation into a desired situation (Hayes 1989). In the current study, the children solved several problems in progressively more complex and less-defined tasks, such as "set up a plumbing system for a two-storey building, so that neither neighbour will complain they are getting less water" or "design and build a water garden". These problems were solved in the physical world, have multiple solution paths and involve the coordination of several physical relations. In knowledge-rich fields such as mechanics in the current investigation, problem solving includes search in the knowledge space in addition to search in the problem space (Hegarty 1991). Thus, design and construction belongs to a class of ill-defined and complex problems in knowledge-rich domains.

For three million years, much of human learning has focused upon solving problems in the physical world, this knowledge multiplying while new aims are constantly formed. Such understanding is formulated as experience-based local rules of action, or as more general rules, spanning the continuum between "rules of thumb" and technological theories (Mitcham 1994). A unique property of this knowledge is the difficulty in articulating it explicitly, as it is, according to Polyani (1966), a kind of tacit knowledge. The richness and complexity of knowing-in-action is not always captured in words (Schön 1983). Its expression is in the actual doing, which changes from moment to moment and is difficult to "freeze" in verbal descriptions (Bamberger 1991). The question addressed in this paper concerns the learning of science while constructing artefacts—understanding described in terms of experience-based rules relating perceptible physical features of the system (such as the height of a pipe) and the resulting flow of water. As such, these rules may be encapsulated in action with no access to articulated forms of knowing, they may be explicit yet remain only within the local context of the built system, or these rules may be more generally applicable to systems outside the range of experience. In fact, countering the above-described research supporting learning through building, there is also accumulating evidence in the literature showing that constructing artefacts does *not* always result in learning the related science concepts (understanding of current among ninth-graders constructing solar-powered boats, Venville et al. 2003; understanding of levers and mechanical advantage among mechanical engineering undergraduate students constructing a variety of elementary mechanisms, Miller 1995; Petrosino 1998; Sherin et al. 2005; more informal reports: Benenson 2001; Sadler et al. 2000).

One of the main arguments against such learning activities rests on cognitive claims regarding learners' limited processing capacities (Miller 1956). The central claim of Cognitive Load Theory is based on studies that show that both solving problems and learning new content may be too great a task for learners (Sweller 1988; review: Paas et al. 2010). The two processes, conceptual learning and problem-solving are distinct, each of them requiring considerable cognitive demands so that they cannot take place simultaneously. Given the problem-solving nature of the construction tasks in this study and the children's non-scientific concepts regarding the related science knowledge, one would expect that little conceptual learning would take place through building. These constraints are exacerbated by young learners' more limited capacity (Case 1987) and limitations in coordinating data and theory (Klahr et al. 1993; Kuhn 1989; review: Zimmerman 2007). Finally, the task itself: the sophistication embodied in even the simplest device presents a complex of multiple parts, relationships and considerations, challenges young children's typically one-dimensional reasoning (Siegler 1978).

These claims are countered with three main arguments regarding the construction of physical systems, addressing the roles of external memory storage, sensorimotor learning and function in structuring both problem solving and learning.

The first argument begins with the claim that the constructed system provides an *external memory* storing previous decisions and steps. This external memory reduces the load on a builder's memory and offers cues and indexes for knowledge states, thus facilitating the incorporation of several physical relations into one's reasoning (Hegarty 1991), particularly in more complex problems (Helstrup and Anderson 1991). Parziale (2002) has studied middle school students' construction of bridges. He describes how the concrete artefact supports the coordination of several ideas into a growing and increasingly complicated system even when these ideas are not necessarily coordinated in the students' articulations. In building physical systems, the problem-solving process is externalized through actions upon evolving concrete forms, thus freeing up mental resources.

The second argument focuses on the *concrete*, *physical and manipulable* aspects of the constructed system claiming their support for learning. In terms of Piagetian theory, these features afford the activation and construction of perception–action schemes through acting on the system directly, observing and "handling" the results of such actions. Sensorimotor learning is a central learning modality among young children (Piaget 1970), throughout their development (Gibson 1991), and among adults in novel and complex situations (Granott 1991; Reiner 1999). More current theory that relates action and perception to cognition includes embodied cognition and more broadly, grounded cognition (Barsalou 2010). According to this view, core representations are grounded in the environment, situations and the body. From this perspective, the cognitive system utilizes the environment and body as information structures. In developmental psychology, Thelen and Smith (1994) have demonstrated how the environment, the body and motor systems play central roles in the development of intelligence. These features of the manipulated physical system—varied action, observable and immediate results—situate it as a prime setting for learning physical knowledge among young children (Kamii and DeVries 1993). This experiential learning forms the basis for representations and abstractions in the development of the individual (Piaget 1970; Fischer 1980). Metz (1993) and Druyan (1997, 2001) demonstrate how young children's body-centred interactions with a mechanical system eventually help generate new knowledge structures. Thus the sensorimotor channel of action, handling and observation of results is conducive not only to learning of sensorimotor schemes but to further representations and abstractions.

The third argument is that the system's *function* lends coherence and meaning to the activity at hand, thus facilitating reasoning with a myriad of components and their interactions. The children in the study are engaged in building an artefact, a working water system. As such, human-made systems are perceived, named, categorized and acted upon mainly according to their function (Gentner 1978; Nelson 1973), over-riding structural or visual similarity; although it is questionable whether this is true regarding younger children (Kemler Nelson 1995; however, see: Diesendruck et al. 2003). The purposeful nature of the use and creation of artefacts supports *structuring* of the complexities at hand, provides meaning and organization to the system's parts and their inter-relations, as well as relevance to the multiple variations one makes upon the system. Such hierarchical structures have been found to support a deeper understanding (Ausubel 1968; Eylon and Reif 1984).

The issue of *transfer of learning*, the ability to extend what has been learned in one context to new contexts (Bransford et al. 1999) is examined in the current study. One of the central critiques of working with concrete materials towards specific goals is that learning taking place is of a local nature, particular to the context in which it is used. This argument comes from studies into technological problem solving described above and from the situated cognition paradigm (e.g. Lave 1988; Lobato 2003; however, see Greeno 2006). In fact, several factors in the study's situation would seem to hinder transfer of knowledge to new situations: *mindful abstraction*, a condition for "high road transfer" (Salomon and Perkins 1989; Sweller 2003) and *explicit analogical reasoning* (Gentner 2005) are not part of the designed learning situation as there is no teaching of schema or direct instruction of principles; the building tasks involved constructing with the same components, so that problems were solved within a *limited context*; the very *concreteness* of the activity and its goals, or their over-contextualization, may impede transfer (Gick and Holyoak 1983); *social context* with peers that could encourage self-explanation was lacking (Hatano and Greeno 1999; Campione et al. 1995). On the other hand, some conditions in this study's setting could support transfer: while "high road" transfer may not be supported, "low road" transfer could be provided for via *several opportunities* that were offered to the children in which they could experience applications of the physical principles; *feedback* to their ideas was provided by the constructed system's operation; the children were *actively engaged* and in the interviews they were encouraged to *generate explanations* for their ideas (Chi et al.1989; Siegler 2002; Rittle-Johnson 2006); while *self monitoring* was not specifically encouraged, obtaining results from the constructed system provided external monitoring of their ideas, as they proceeded to change systems that did not "work"

(Ericsson et al. 1993); finally, transfer among young children is seen when their learning of the source domain is *causal* rather than superficial, a condition this study hoped to support (Brown 1989; Brown and Kane 1988; Barnett and Ceci 2002).

Given the conflicting evidence and theory regarding whether building results in science learning and the mix of supporting and impeding conditions for transfer of such learning, this study sets out to examine the two issues.

Children's understanding of water physics

From a very young age, children experience water in motion, in bathtubs, through faucets, in bottles and glasses. While the topic of hydrodynamics is not part of elementary science curriculum, activities with water are common in preschool classes (Kamii and DeVries 1993). Moreover, early experience with water systems may form the basis for a later understanding of pressure, and systems that involve fluid flow, e.g. water bodies in ecosystems and the circulatory system.

Few investigations have been conducted into people's understanding of water flow (Ibanez and Ramos 2004). In research related to students' ideas regarding hydrostatics, the concept of pressure in a liquid has been explored more extensively, showing that even among high-school and undergraduate engineering students there are deep confusions and overlap between force/weight and pressure concepts (Besson 2004; Engel Clough and Driver 1985).

Young children identify liquids as "runny" materials that can be poured, with water as the exemplary liquid (Stachel and Stavy 1985). Regarding gravitational effects, children believe water can go only down and they can qualitatively describe its flow (Piaget 1956; Ackerman 1991). Among elementary students' drawings of rivers, two-thirds indicate height differences (e.g. water source and river basin) in the river's flow (Dove et al. 1999). Brophy and Alleman (2003) have explored knowledge of home utilities and found that most of the younger students knew that water came from external sources and was led through pipes; however, very few students across the ages and none among the younger ones were aware that the water needs to be pressurized, e.g. by being transported to a water tower first.

The understanding of how multiple subsystems or branches in water systems relate and interact with respect to flow in the system is approached in the current study. As the children constructed with systems that split from a main source into at least two branches, understanding that increasing resistance on one branch increases the flow in the other branch is critical to making sense of the system. No previous studies into the topic have been found. One may compare conceptions of such systems with those of branching in electrical circuits. Research has reported that even many physics undergraduates reason locally in a unidirectional way about such branching, i.e. the current splits evenly at intersections, rather than according to the relative resistance on each branch (Shipstone 1985; Duit and von Rhöneck 1997); younger students—fourth graders concluded that the current will go only through the path of least resistance, rather than splitting between the branches (Shipstone 1985). These findings point to the fact that junctions and branches in systems may be difficult to comprehend in a global way. Moreover, given young children's more limited memory capacity, one may assume that some limits exist regarding the *number* of interacting subsystems young children can reason with.

To conclude, research regarding people's understanding of fluid flow is limited, demonstrating older students' difficulties with the concept of pressure and simple gravitational principles and unidirectional perception of branching descriptions of flow. Research into how students perceive flow, particularly features related to the dynamics of natural and artificial water systems is yet lacking and is advanced in the current study.

Young children's inference of physical rules

During the interviews in this study, the children were presented with tasks that required them to imagine two streams of water coming out of a system, predict how they compare and explain their prediction. Through this design, the rules the children use in predicting the system's output are elicited—rules, set in terms of how different system features (height, width and resistance of the pipes through which the water flowed) impacted the flow of water. Extending the idea of technology knowledge formulated as rules or laws, this study focuses on the children's evolving explanations of water flow framed as rules.

Two lines of research are informative with regards to younger children's ability to infer rules from experience: causal inference (e.g. Sobel et al. 2004; Cheng 1997) and scientific reasoning (e.g. Klahr and Dunbar 1988; Schauble 1990; Zimmerman 2000). Both share the goal of discovering how people make inferences of causality from data on co-variation (Kuhn and Dean 2004).

With respect to *causal inference*, different models describe how the rules are inferred from data (Shanks 1995; Cheng 1997; Sobel et al. 2004). Gentner and Medina (1998) suggest that the process of comparing several instances of evidence and finding their common features affords a mapping and alignment between structural similarity and a symbolic rule-based account. In this study, one may assume that the co-occurrence of the constructed system's features and its outpouring water provides a database of correlated evidence that should play a part in constructing associations and aligning them with a causal rule-based account.

The second line of study, *scientific reasoning*, is greatly influenced by the earlier work of Piaget and Inhelder (1948/1956). Their distinction between concrete and formal operational thought led them to conclude that that the logic of scientific experimentation and inference is not acquired until adolescence. In several studies exploring young children's scientific reasoning (Klahr et al. 1993; Schauble 1990; Kuhn 1989), it was observed that they could not entertain more than one hypothesis at a time, conducted experiments that were difficult to interpret, had trouble inferring implausible conclusions, persevered with prior beliefs in the face of conflicting evidence and lacked valid heuristics in coping with this discord. These studies suggest that inferring rules from data may be too difficult a task for young kindergarten children.

Conclusion of literature review

Several inconsistent conclusions were presented in the review: whether or not science knowledge is learned through designing and building related artefacts, whether transfer of learning takes place in such learning environments and contradictory evidence regarding young children's ability to infer rules from experience. Moreover, some related topics have been insufficiently investigated: students' understanding of fluid dynamics and preschool children's learning of science through building.

The present study addresses these issues and explores Piaget's conjecture (Piaget 1956; pp. 233–234): "It is in *making things* and in seeing them made that the child will learn the resistance of external objects and the necessity of mechanical processes". It explores how making mechanical testable systems may support conceptual learning of science.

Purpose and research questions

This study focuses on the construction of physical systems and explores its potential for learning science among preschool children. The following research question guides this study:

How does building dynamic water flow systems impact young children's understanding of water flow, in terms of:

(a) *Understanding* the physical rules: individual rules, consistency in reasoning with these rules and the relative importance assigned to the rules?
(b) *Coordination* between: rules in multivariate tasks, sub-systems in analyzing flow and height and gravity relations across large systems?
(c) *Transfer* of learning?

Methods

Fifteen children worked individually with the author outside of class and built water-pipe systems during four sessions that included end-of-session interviews. In addition, they were interviewed with a pretest and posttest. A control group of fourteen children were interviewed to control for testing, maturation and familiarity with the interviewer.

Participants

Thirty children participated in this study, sixteen girls and fourteen boys, selected randomly out of 145 children in an urban middle-class school in the central area of Israel with a medium–high Social-Economic Status. The children's ages spanned 5 years, 2 months to 6 years, 3 months; $M = 5$ years, 8 months, SD $= 3$ months. The children were randomly assigned to one of two groups: an experimental and a control group (8 girls, 7 boys in each). The children's parents all signed consent forms approving their child's participation in the study. One girl from the control group dropped out after two sessions following loss of interest and is not included in the analysis.

Experimental design

The design is a quasi-experimental pretest–posttest control group design with random assignment (Fig. 1). The children participated *individually* in a pretest, intervention, and posttest with the author as interviewer. During the intervention, the experimental group children constructed water systems along four different sessions, spaced about one week apart, each session ending with an interview. The interviews included several prediction tasks regarding the flow of water and no feedback was provided—neither by operating a system, nor verbally. To eliminate effects of testing and maturation, a control group participated in the pretest and posttest. To control for familiarity with the interviewer, an important factor when interviewing young children, the control group engaged in four inquiry-based activities on topics unrelated to the experimental group's intervention; astronomy and mythology. This design, while not addressing a comparison with other forms of learning about water flow, targets a central aspect related to the main research question. This study focuses on children's learning through building with no additional interventions. However, it stands to reason that the six interviews throughout the experimental period would impact the children's reasoning

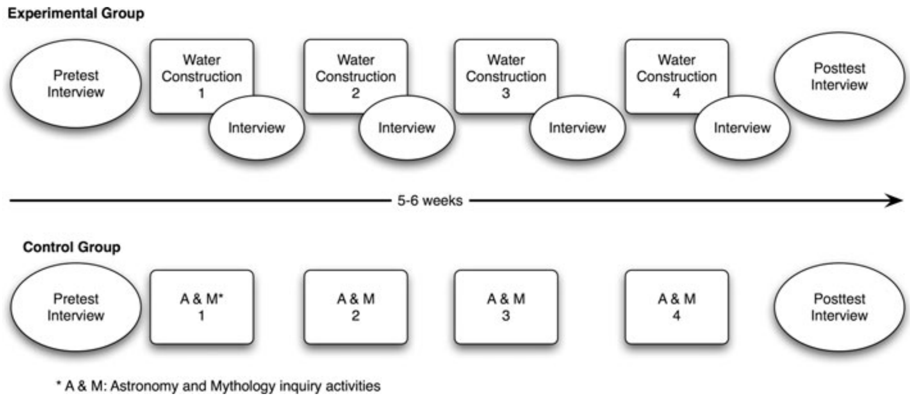

Fig. 1 Design of the study

and learning about the target content. As will be shown, this choice resulted in an observation of a phenomenon pertaining only to the effect of testing.

The children participated in the activities and were interviewed individually on an open porch outside the school science laboratory. The pretest and posttest lasted 30–40 min; the intermediate sessions were devoted to 20–40 min of construction and a 15–20 min interview. The sessions were all videotaped.

Intervention

The intervention is described with respect to the construction set, the construction tasks and the end-of-session interviews. The researcher's roles during the intervention involved: (1) presenting the construction kit by explaining and demonstrating the functions of various components; (2) setting the goal for construction; (3) minimally assisting during construction when a hurdle was met and (4) interviewing the child in the pretest and posttest sessions and at the end of each session.

Construction set

A construction set for building large water pipe systems was developed by the author. It is modular and transparent, easy to construct with and its components enable creating a large variety of systems. The water reservoir is a plastic bag and can be hung at different heights on a tall plastic-coated metal net. Large plastic-coated metal net blocks of varying sizes are used to create the topographical structure (e.g. a two-storey building, the three hills in Fig. 2b). Several transparent pipes are laid out, sorted by sizes. A toolbox contains several components, commonly found in chemistry laboratories (valves, splitters, connectors, pipe-ends, flow measuring devices) that connect to the pipes and to the blocks (Fig. 2a). In addition, two components were manufactured specifically for the set: a water-resistor and transparent containers that could be connected between two pipes. Construction with this set allows creating pipe systems that connect to the topography, branch and deliver water to several locations. The rate of water delivery is controlled by valves, the routes defined by the hierarchy and branching of the system, and several factors related to height and resistance. In Fig. 2b, the reservoir's water (top-left) is piped to three "hills", going up and down repeatedly, all the way to where the child is standing.

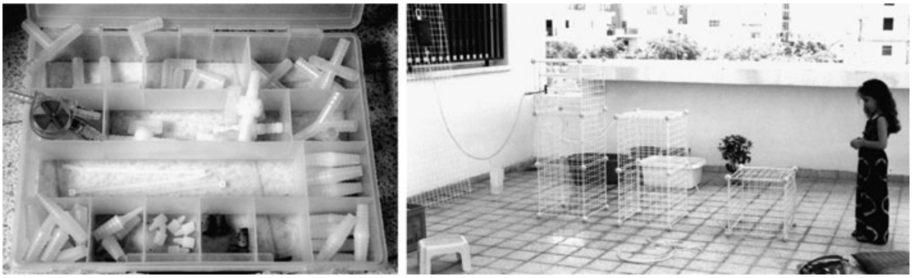

Fig. 2 Toolbox and sample construction of a water system

Understanding children's ideas about water flow necessitated reformulation of the physical principles so that they would map onto experienced sensorimotor rules. These "rules of thumb" are comprised of body-based actions and their easily perceived outcomes, which may develop through interaction with such systems (Mitcham 1994). The topic of fluid flow is usually studied among high school or college students specializing in mechanics. Its principles are typically presented and formulated in terms of conservation of energy (Bernoulli's Law), with pressure as a central concept. These principles together with Poiseuille's Law were used to derive how the rate of flow is modified by variations in the system. References to rate of flow should be taken to mean the volumetric flow rate (the volume of water passing a given point per unit time). The three central variables impacting the rate of flow are: *height* difference between the water level in the reservoir and the pipe's exit, exit *hole* size and *resistance* along the path of flow (hence, abbreviated to height, hole and resistance). Table 1 presents the three rules that describe the causal structure relating these variables to fluid flow. The table describes three progressive viewpoints, and foreshadows some of the findings. The expert viewpoint states the rules in qualitative terms and is based on the scientific literature and verification with experts (see section on reliability). The children's viewpoints are termed as "inexperienced" and

Table 1 Causal structure of factors impacting flow rate as viewed by inexperienced and experienced children and by expert adults

Varied feature	Inexperienced	Viewpoint experienced	Expert
Height of pipe-end	High raises the flow rate, or; height does not impact flow	Low raises flow rate	Larger difference between entering and exiting water height, assuming continuity of water body in pipe, raises flow rate
Hole-width (cross-sectional area of pipe-end[a])	Large raises flow rate	Narrow produces faster or farther streams	No effect on flow rate; narrow produces faster and narrower streams
Resistance of pipe (rises with pipe-length, number and sharpness of curves)	More raises flow rate, or; resistance does not impact flow	Less raises flow rate	Longer and/or more curves, and/or sharper curves decreases flow rate

[a] The smallest pipe-end cross-sections were wide enough, so that frictional effects are negligible. The construction set operates in the regime of laminar flow and turbulence is relatively infrequent

"experienced" based on categories that emerged in the study's data. An "experienced" view describes the closest the children had approached the scientific viewpoint towards the end of the experimental period. An "inexperienced" view describes explanations found earlier in the study, which are also farther away from the expert view.

Construction tasks

A sequence of four building tasks was created, using the construction set as a semi-open learning environment (Table 2). The tasks were designed for a gradual increase in (a) the number of parallel units and controls in the system's branching; (b) the number (from one to three) and kind (from resistance, through height to hole) of physical rules that were necessary for understanding a successful solution. The tasks were also designed for feasibility and success: the children could complete construction within 20–30 minutes with at least moderate success.

Instruments

A series of structured interviews and protocol were designed to follow the children's learning. This study focuses on the results from the pretest and posttest, to highlight the overall learning results. Additional studies were conducted into the learning progressions and will be reported separately. The pretest and posttest interview items consisted of problems, most of which involved predicting how two streams coming out of a system

Table 2 Construction tasks, possible solutions and related concepts

Session	Goal	Possible solution	Concepts[a]
1	Plant watering system: two plants, big (more water) and little (less water), over prolonged time	From the water source, the pipe is split in two; resistance is loaded to reduce flow; greater resistance is loaded near the smaller plant	Splitting the system in two Resistance rule
2	Plumbing system: two apartments, high and low; same amount of water	From the water source, the pipe is split in two, loading resistance on lower apartment	Splitting the system in two Resistance rule Height rule
3	Color mixing machine: lead water with three different colors into three fixed containers; mix colored water from containers into a single vessel below them	From the water source, the pipe is split into three; a valve on the main pipe and on each of the three pipes; each pipe is connected to one vessel; each vessel has a pipe leading out, with a valve or plug	Splitting the system in three Differential control of the paths of flow
4	Water garden: multiple pools and fountains. A book on Italian water gardens was used to inspire some of this work	Most systems involve splitting the main pipe at several points, incorporating intermediate vessels, creating multiple exits with different pipe-end widths	Splitting at multiple locations Resistance rule Height rule Hole rule

[a] The minimal set of concepts related to the possible solution

compare and explaining this prediction (Appendix). The interview consisted of two parts. The first part included items in which a physical system was displayed and discussed. The physical system was made of the same parts the children had built with but was not operated during the interview. The second part comprised the same items as in the first part in the form of schematics. The children drew the water streams onto a schematic of the system, and then proceeded to describe and explain their drawings. This repetition was designed to increase the probability of capturing the children's best reasoning and to test for consistency.

The test items themselves were planned to probe the children's understanding of the three physical rules (Table 1) and their combinations. The pretest and posttest included several equivalent items (three single-variation tasks; two double-variation tasks in the pretest, four in the posttest; one transfer task, one branching pipes task) and some that were used in only one of the interviews (one on familiarity with home water systems in the pretest; two on coordinating the height rule across the system in the posttest). Single-variation items involved comparing streams emitted from a system with one variation (height, hole or resistance). Double-variation tasks involved systems varying two of these dimensions. For example, in Fig. 3 the system forks into two pipes, differing both in height and resistance. The lower pipe, which would have provided a greater flow rate if the resistance were equal, is loaded with extra resistance.

The order of the questions in the first part of the interview was planned for the shortest transformation times between tasks, as the same parts were reused. The items in the second part, using schematics, were presented in one of three randomized sequences. A single-variation task was always presented first. In the pretest, a simple system with one pipe and no variations was first presented, described and operated, so that the subsequent questions would be grounded in an experience of water flow. No feedback was provided verbally or by operating the system.

Single-variation items were used to test the children's understanding of the individual physical rules. Double-variation items were used to test their ability to coordinate the physical rules. Young children's coordination of parallel sub-systems was explored using

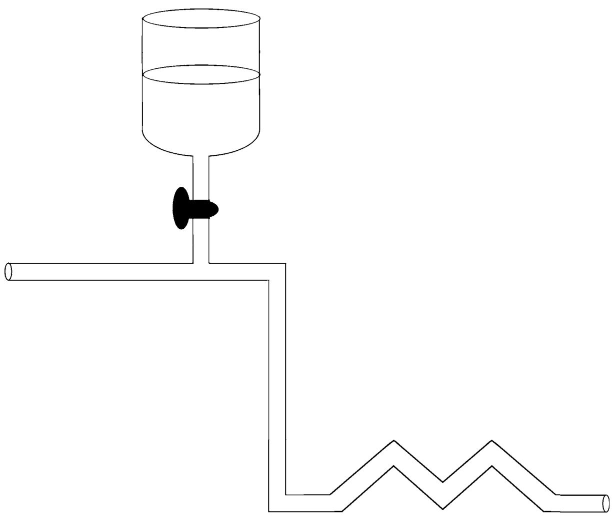

Fig. 3 Height and resistance variation task

the branching pipes in the Appendix. A single pipe is split in two, and each of these is further split in two. Valves are placed in an asymmetrical array. The system's operation is demonstrated with all valves open. The main valve is then closed and different valves are opened and closed. The child is asked to predict whether and from which pipes the water would exit, or, whether particular stream combinations were possible. Coordinating the impact of height and gravity across the system was explored in the posttest with two items: "watering a higher plant" asks whether water would come out of a pipe whose end is higher than its reservoir; "connected vessels" asks what would happen in a system with two connected vessels at different heights. To test for transfer, the children were asked to compare the water coming out of faucets on the first and sixth floor in a nearby building, using an identical protocol to that described above. The pretest included a question probing the children's prior knowledge of home water systems. Both tests incorporated a spatial test as well (water level task, Piaget and Inhelder 1948/1956). The latter are not reported on here.

Data analysis

Data analysis focused on data collected in the pretest and posttest interviews and was comprised of two phases. The first phase involved content analysis of the children's predictions and explanations, resulting in identification of their conceptions. The second phase entailed statistical testing of the identified conceptions across groups and tests.

Content analysis

In exploring the children's understanding of the water flow rules, the children's predictions and explanations were coded as inexperienced or experienced (Table 3).

Since a child had between two and three opportunities to explain his or her thinking for a single task, the highest-level answer was coded for. Its consistency was coded as well, and is defined as the proportion of times this answer is provided out of all opportunities.

The relationship between the physical rules in the child's perception tested their attribution of causality to the system variations. The system features they mentioned in their explanations of the single-variation tasks were coded. Examination of the alignment between the task variations and these dimensions allowed testing for biases.

The children's coordination of rules is analysed as the number of rules they articulated in explaining their predictions for the double-variation tasks, disregarding the rules' correctness. Two excerpts demonstrate the coding. A *single rule* is demonstrated in a height and resistance varying task: "Different [streams]. That this [exit] is lower and this is higher. And when this [exit] is higher so this [stream] is lower". Although both resistance and height are varied, the child explains the predicted differences employing a height rule alone. *Two rules* are provided in the following prediction and explanation of a hole-width and resistance varying task: "Different. Here [short pipe, narrow hole] it's straight [marks stream going vertically down] and here [long pipe, wide hole] it's crooked [marks forward and then downward motion of water stream]. The round line [long pipe, wide hole] is a longer pipe and this pipe is shorter. Here the opening is smaller and here the opening is bigger. A shorter pipe—a larger amount. A bigger hole a bigger amount. The same!!" The child gradually coordinates two rules in reasoning about the system: shorter pipes bring more water and bigger holes supply more water. Seeing that each of the two rules provides a contradictory prediction, she concludes that the streams have a similar flow, even though they do not necessarily have the same shape.

Table 3 Coding scheme for children's explanations and representative answers

Varied feature	Inexperienced view		Experienced view	
	Definition	Example	Definition	Example
Height of pipe-end	High raises the flow rate	"More [water] from higher one. [Streams reach] farther from top. Because it has more room to go down"	Low raises flow rate	"Here [lower exit], more water comes out. Because here [marks pipe to lower exit] it goes down down [sliding motion]. Because of that I did this [stream] fat one"
Hole-width (cross-sectional area of pipe-end)	Large raises flow rate	"More [water] in the bigger exit. Here [marks wider exit] there is a bigger stream because the hole is larger and here [there is] a little water because the hole is small"	Narrow produces faster or farther streams	"This [narrow exit] farther. This [wide exit] a little closer. Because the water here [wide exit] has a big hole and here [narrow exit] a little hole"
			No effect on flow rate; narrow produces faster and narrower streams	"This [wide exit] comes out folded [curved downward arc] and this [narrow exit] comes out straight [greater horizontal distance]. Same amount of water. Because to this reaches the same water and to this reaches the same water"
Resistance of pipe (rises with pipe-length, number and sharpness of curves)	More raises flow rate	None found	Less raises flow rate	"That this [more folds] comes out a drop of water and here [less folds] an awful lot. Because the pipe was folded and here the pipe wasn't folded. The folds block the water a little"
	Resistance does not impact flow rate	"Similar. Because it doesn't matter if it's straight [folded or straight]. Both are small holes"		

Coordination between sub-systems was explored with the questions regarding the branching pipes system in the "Appendix". From these, one can surmise whether the children correctly predicted at the level of no, single or double branching, and could reason with one, two or four parallel routes.

Coordinating the height rule across the system was explored with two items "watering a higher plant" and "connected vessels", described above. The children's responses were coded in two forms. One was whether their prediction corresponded with the scientific view. Another examined their explanations and formed categories that capture the main thrust of the children's arguments in justifying their predictions.

Statistical analysis

Several statistical tests were used to examine differences between the groups (one-way ANOVA, unpaired t tests, Hedge's effect size), changes from pretest to posttest and among items in a single test (paired t tests), and for correlations between possibly related variables. The Chi-square goodness of fit test was used to test the alignment between the children's explanations and the task variations. These are described in more detail in the results section.

Validity and reliability

Content validity was established with respect to the construction and interview tasks in the following way. Two mechanical engineers, experienced in teaching and creating curricula in pneumatics and hydraulics, tested the construction system, and examined a large collection of interview tasks and the analysis categories. With respect to the construction set, they confirmed that the scientific interpretation of the physical rules described in Table 1 is correct and central to a causal understanding of the topic. They reviewed the proposed interview tasks, excluded some tasks as too difficult, simplified some tasks and suggested additional tasks. Finally, they assessed the analyses categories and found them appropriate.

Reliability was determined by having three independent coders (the author and two graduate students) code 30% of the transcripts. Inter-rater reliability between the raters for this portion of the data was 0.91 for coding the children's rules and 0.96 for identifying the causal features.

Findings

The results regarding children's learning through building are presented with respect to the three above-described dimensions: the children's understanding of the physical rules, three forms of coordination in reasoning and transfer of their learning to new situations.

Understanding the water flow rules

How did the children's understanding of the physical rules associated with the systems they constructed change? Moreover, how stable and consistent were these changes? Finally, what system features are causal in the children's perception of the system's workings? This section addresses the children's conceptual understanding as it grows through building and is compared with the control group.

Understanding the physical rules

The single-variation items were used to gauge understanding of the separate rules. Pretest differences between the groups and genders were tested using a one-way ANOVA. No significant differences were found between the two groups ($F(1,27) = 2.175, p > 0.1$), nor between genders ($F(1,27) = 0.246, p > 0.1$); and so these results were merged.

The results (Table 4) indicate major shifts in the builders' understanding of how height differences and changing the hole size impact the flow of water, rising from 21 to 80% regarding the height rule, and from 10 to 73% with respect to the hole rule. A third of the experimental group in the posttest demonstrated a more advanced form of the hole rule, in which narrower holes produce both farther/faster *and* narrower streams. Similar changes were not observed for the control group. The children mostly understood the resistance rule

Table 4 Descriptive statistics of participants' understanding of the physical rules on the pretest and posttest interview items

Group rule	Pretest	Posttest	
	All mean (SD)	Experimental mean (SD)	Control mean (SD)
Overall	38 (26)	76 (27)	38 (32)
Resistance	83 (38)	73 (46)	57 (51)
Height (main[a])	21 (41)	80 (41)	36 (50)
Hole	10 (31)	73 (46)	21 (43)
Consistency[b]	71 (25)	66 (23)	65 (23)
Height (transfer[c])	10 (31)	13 (35)	43 (51)

Reported findings are the percentage of children whose highest-level response corresponds to an "experienced" view in Table 1

[a] The main task refers to the height-varying items in the interviews in the main body, which was conducted using the same system components the children had built with

[b] Consistency is defined as the proportion of times the highest-level answer is provided out of all opportunities

[c] The transfer task is a single item in the pretest and posttest that referenced a nearby real-life high-rise building

from the start, and regressed in this understanding from pretest to posttest, more notably in the control group. It is important to note the large standard deviations in the results. This indicates that while on the average, large differences were observed for the experimental group, the children in both groups were diverse in their understanding of the relevant concepts.

To compare between the two groups, gain scores were used as dependent variables, thus avoiding the impact of individual differences in the pretest. Gain scores were defined as the difference between the posttest and pretest overall score (%). The experimental group's learning gains were large ($M = 44$, SD $= 39$) and the control group's learning gains were null ($M = -7$, SD $= 37$), demonstrating a strong effect size (Hedge's $g = 1.30$, CI $= 0.50$–2.10).

Consistency in reasoning with the physical rules

Consistency was defined as the proportion of times the highest-level answer is provided out of all opportunities. The consistency in the children's use of these rules was relatively stable between the tests, roughly two-thirds of the cases, with no significant difference between tests or between the groups (Table 4). The correlation between these scores and their consistency, disregarding session and group, is a moderate Pearson $r = -0.326$, $p < 0.01$ (2-tailed). This reciprocal relationship reflects the fragility of the children's higher level (and usually new) understandings. The seeming contradiction between this reciprocal relationship and that no change was observed in consistency from pretest to posttest is resolved when viewing the actual means. From pretest to posttest, both groups decreased their consistency, however this is a relatively weak effect, not reaching statistical significance. Only in relating to the scores is this moderate correlation exposed for the experimental group. Among the builders, consistency was slightly reduced in the posttest, and this is correlated with higher-level rules they had recently learned through building.

Causal status of the physical rules

This section explores the children's attribution of causal status to the system's features. The single-variation tasks' variation (e.g. height) was compared with the children's explanations. The frequency at which each system dimension (height, hole, resistance) was used in justifying a prediction is described. These frequencies are described for both groups together in the pretest ($N = 29$), and for the builders in the posttest ($n = 15$). In the pretest, justifications for judgments are mainly task-relevant (97% for resistance varying tasks, 89% for height, 98% for hole). However, in the posttest, the picture changes. Hole-based justifications crop up even when this feature is not varied and as a result, the justifications are not as frequently task-relevant (73% for resistance varying tasks, 70% for height, 100% for hole). For example, in the pretest, when comparing the streams from a folded and a straight pipe, a child demonstrated her understanding of the resistance rule. She explained that the curves in a folded pipe partially block the water, causing the stream to be smaller: "That this [folded pipe] comes out a drop of water and here [straight pipe] an awful lot. Because the pipe was folded and here the pipe wasn't folded. The folds block the water a little". In the posttest, for a comparable task, the very same child predicted that the two streams would be similar, basing her explanation on the size of the holes at the end of the pipe: "Similar [streams]. Because both have a small hole".

The Chi-square goodness of fit test was used to explore whether the builders' explanations align with or deviate from the actual task variations. In the pretest, alignment was observed ($\chi^2(2, n = 144) = 1.5, p > 0.1$) and no preferences were detected. In the posttest, clear preferences are observed: hole > resistance > height, and the experimental group children's responses significantly deviate from the task variations ($\chi^2(2, n = 75) = 7.0, p < 0.01$).

Summary: understanding the water flow rules

The experimental group developed significantly better understandings about water flow after engaging in a series of building activities. The rise in scores is due mainly to shifts in understanding of how height and hole-size impact the water flow. The resistance rule was understood by most of the children from the start; however, rather than an expected ceiling effect, a regression is seen for both groups, stronger for the control group. No changes were observed regarding the children's consistency in reasoning; nevertheless, to some extent higher-level rules were associated with lower consistency, showing that these newly minted understandings are not yet robust. The children's perception of causality among the system features grew more biased during the experimental period. In the pretest, the children referred to all varied system features in their comparisons, predictions and explanations; however, in the posttest, a single feature (the pipe-end hole-size) overrode some of these considerations.

Coordination

Several kinds of coordination are necessary for a deeper understanding of the water flow in such intricate systems.

Coordinating the physical rules

How complex was the children's reasoning? The children's coordination of two physical rules is explored. Specifically, the number of rules they articulated in explaining their predictions of the system's behaviour for the double-variation tasks was coded. In the pretest, the children explained their predictions using mainly one rule ($M = 1.02$, SD $= 0.38$). In the posttest, the control group continued explaining with one rule ($M = 1.01$, SD $= 0.38$); however, the experimental group increased their ability to coordinate two rules ($M = 1.23$, SD $= 0.47$), so that a quarter of the responses in the posttest demonstrated this coordination. Every single child in the experimental group coordinated two rules at least once in the posttest. An intermediate effect size (Hedge's $g = 0.50$, CI $= 95\%$) describes the impact of building upon the extent to which rules are coordinated in the children's explanations.

Coordinating parallel sub-systems

The children's coordination of several components in a system is considered. The number of parallel routes the children could reason through in a single system was explored. The number of paths the children could work through was the same in both tests for the experimental group (paired $t(14) = -0.972$, $p > 0.1$) and was similar for both groups in the posttest (unpaired $t(27) = 0.794$, $p > 0.1$). The mean in the pretest is close to two branching pipes ($M = 2.21$, SD $= 1.01$), and in the posttest is only slightly higher ($M = 2.66$, SD $= 1.01$).

Coordinating height and gravity across the system

Understanding that raising and lowering the pipe-end impacts flow does not necessarily mean that a complete grasp of how height and gravity are coordinated is reached. This understanding was probed more extensively in the posttest, using two items: "watering a higher plant" and "connected vessels".

No differences were found between the two groups (unpaired $t(27) = -0.072$, $p > 0.1$ for the first item; unpaired $t(27) = -0.523$, $p > 0.1$ for the second item); consequently, findings are described for the whole sample. For the item "watering a higher plant" the mean score was low ($M = 14$, SD $= 35$); for the "connected vessels" item, the mean score was only slightly higher ($M = 24$, SD $= 43$). No correlation was found between the children's understanding of how changing the height of the pipe-end impacts flow, and the understanding expressed in these tasks. However, the correlation between the scores for the two tasks is high (Pearson $r = 0.709$, $p < 0.01$ (2-tailed)), demonstrating they are tapping onto the same reasoning models.

The children's explanations were further explored in terms of the main thrust of their justifications. These justifications were coded by categories arising from the explanations themselves in the following way.

One type of explanation focuses on the path of flow. Flow is limited only by the path created by the tubes in the system; the water moves through the system from beginning to end, all of it coming out the end: "*if there's path, there's a flow*". Watering a higher plant is possible, e.g. "Possible. You open the valve and it [the water] all comes out". The water all exits the system with connected vessels, e.g.: [Marks route till the exit of the second box] "Everything will come out".

A second type of explanation considers the path of flow, but subordinates it to gravity considerations "*water cannot go up*". Once reaching a low point, water cannot flow upwards. Water cannot reach the plant because it gets stuck at the lowest point in the pipe: "[The water] won't reach it [the plant]. Because it makes a curve like this [shows imaginary pipe on the floor] and can't go up anymore [from the floor]". For the connected vessels array, the water reaches the lowest point between the boxes and stops: "It [water] won't pass to here [second box]. It will collide here [marks bottom of U-shaped pipe connecting the boxes] and won't pass".

A third type of explanation coordinates these two considerations. Water flows through the pipes that support the path of flow. This flow is partially limited by gravity through a global view that considers the height of the water source as limiting. This is the "*coordinated*" view. Water flows downwards and upwards until equal levels are reached. In the task asking whether a plant higher than the water source can be watered, this view claims that water cannot reach the plant because the plant is higher than the water source: "Only if you raise the bag [the water will reach the plant]"; "Impossible. Because the water cannot go up a lot a lot a lot. They can only go up a bit". In the connected vessels task, the common horizontal is marked, e.g.: [Marks route of moving water. Shows common horizontal level for the two boxes]: "More in low box and less in high box".

Among both groups, 17% of the children expressed different explanations for the two tasks and are categorized as inconsistent; 55% demonstrated an "if there is a path, there is a flow" view; 21% explained that "water cannot go up"; 7% expressed a "coordinated" view.

Summary: coordination

Single rules dominated the children's responses both before and after building. However, different from the control group, the builders all showed a budding ability to coordinate two rules in predicting and explaining water system behaviours in the posttest. The number of parallel paths the children could consider in a single system remained the same from pretest to posttest, averaging between two and three parallel paths or sub-systems. Through building, the children learned that raising and lowering the pipe-end results in specific changes in the rate of flow of the emanating streams. In spite of this greater understanding, they did not coordinate this into a more complete understanding of the role of water height in the system, namely the limit placed by the height of the water in the reservoir or the common level of the water in connected vessels at equilibrium. Three types of explanations were found: one based on path availability, one claiming that water can only go down and one coordinating the flow of water with restrictions posed by the water source's height and eventual equilibration within the system (the scientific view).

Transfer

How general was the children's understanding of the physical rules? Did it remain encapsulated in the building parts they constructed with or was it applicable to additional settings? The children's ability to apply the height rule to situations outside of the building situation was explored (Table 4).

While most builders learned the height rule in the context of the construction set, they did not apply this learning to the transfer task (posttest main task and transfer task, paired $t(14) = 2.449, p < 0.05$). Curiously, the control group shows greater success at the transfer task than in the main task (posttest main task and transfer task, paired $t(13) = -2.110$, $p < 0.05$), however less than the builders' success in the main task. It is also interesting to note that although in the pretest, there is an intermediate correlation between the children's predictions regarding height-variation in the main and transfer tasks (Pearson $r = 0.521$, $p < 0.01$ (2-tailed)), no such correlation was found in the posttest ($r = -0.026, p > 0.1$ for the experimental group; $r = -0.240, p > 0.1$ (2-tailed) for the control group). Thus, both experimental and control groups learned the height rule in one context but did not transfer it to a different one from that in which it was learned.

The control group children's greater understanding of water flow in real everyday buildings is surprising. During the experimental period, several control group children approached the author, posing questions about water flow (that were not answered). Three children told her that they had talked with their parents about these topics. Another child took the author under the sink at school and proudly described how the water flows in and out of the system. Evidently, the pretest interview elicited their curiosity, a curiosity that was not sated through experiences with building such systems. Following this, at least some of these children conducted their own explorations on the topic. The children in the building group did not describe similar explorations and their understanding of the height rule in home settings did not advance.

Discussion

When young children are free to choose their activities in preschool, they most commonly prefer construction (Rubin et al. 1978). Design-based learning environments draw upon such activities and extend them to advance students' learning. This study was designed to explore young children's science learning as they built with a novel construction set and expands on previous research into curricula that involve students' design of working devices to younger ages. Furthermore, an understanding of children's concepts of water flow is advanced.

The main thrust of the proposal entertained in this study is that through constructing with carefully designed learning environments young children come to abstract the physical rules underlying their constructions; this learning is limited by cognitive-developmental constraints but partially expands beyond these bounds as intellectual growth involves not only the learning of content in a particular domain, but touches upon structural aspects of their reasoning. This proposal is now examined.

The study provides evidence for young children's intellectual growth through building working devices, demonstrating both large learning gains regarding the related science concepts, and the emergence of a more general ability—reasoning with two physical rules. These rules map onto the manipulations and variations they had performed with the system. While these rules were embedded in their constructions and actions, they could transfer this understanding to solving and explaining new problems presented with the same set of parts.

Boundaries to this learning are evident as well. Although all the children could coordinate two rules, they did not do so at every relevant opportunity. While advancing in their ability to coordinate two rules, they could not coordinate more than two sub-systems, nor relationships involving the height of the water across the large system into a more global view. The extent to which they could use their new learning is limited as well. While they could apply the physical rules they learned to new problems with the same construction system, this ability did not expand outside the building set to other situations. Finally, the children's new understandings were less consistent across tasks than their older understandings. Learning and its limitations are discussed.

Technological knowledge has been described in the introduction as arising from action and spanning the range from experience-based "rules of thumb" to technological theories (Mitcham 1994). The children in this study advanced along this continuum forming rules of thumb, applicable over a wide range of constructions but situated within the context of the building set. They succeeded in extracting the physical rules embedded in their constructions, rules used and re-used in several problem-solving tasks. The findings related to the children's learning gains are consistent with previous research into students' learning with science curricula that include activities involving design and construction. Moreover it broadens these findings to younger ages, for which research on the topic is scarce.

Several claims countering the potential contribution of building to learning and have been described. Foremost is a claim based on Cognitive Load Theory (Sweller 1988), arguing that solving problems and conceptual learning cannot take place concurrently. In this study, the children solved unfamiliar problems by building with a novel construction set involving science concepts, which initially they had mainly misconstrued. Since they had built at least partially successful constructions and also learned some of the related physics rules, it would seem that this claim is not supported in the current study. The following attempts to resolve these contentious results.

It is proposed that modularity along the solution path supports the learning of the individual relationships in the present study. Moreover, it helps push the children's reasoning beyond its maturational limitations, bringing together coordinated pairs of such relationships as they reach out to bridge idea and its physical expression. Previous research has reported on young children's strong preference for one-dimensional rules when reasoning about multi-dimensional problems. In the current study, the children do not frequently go beyond this when articulating their understandings. However, their built constructions surpass these boundaries by far. How are these two resolved? Building involves backtracking when solutions are inadequate, refining them when they seem to be in the right direction and compounding with additional variations once one aspect of the problem has been solved. The previous rounds of changes, refinements and additions are stored in the structure-in-the-making. It is claimed that such external memory storage facilitates both solving the problem (e.g. Parziale 2002) and learning. In fact, one can tackle components of the solution individually and in succession, gradually converging on a satisfactory solution, reducing cognitive load and making way for learning. However, a two-way interaction was observed in this study. While the children usually addressed each variation separately as single rules, building with the system supported an increased ability to coordinate two rules. Of course, not all problems and technologies are amenable to such decomposition. Nonetheless, for a wide range of construction sets this is in fact a possible, if not optimal, solution path. Previous research has identified upward shifts among children at the same age when noticing the relevant features is supported and feedback to their predictions is provided (Siegler 1976), and when provided with multiple induction, deduction and inference problems (Halford 1993). Thus, building supports the children's more complex reasoning by allowing for decomposition of the problem at hand and later coordination.

Additional factors were proposed to further children's learning through building. The *concreteness* of the structure supports learning by virtue of both variations and their results being tangible and observable. The children manipulate the parts, squeezing and raising the pipes. They can touch and feel the streams coming out (and often do) as well as see them. These variations gradually move away from their manual manifestation and transform into structural features in the systems. Availability of such sensorimotor learning serves conceptual learning both in helping notice the relevant features, variations and their outcomes (Siegler and Chen 1998) and in associating them with each other. Sensorimotor schemes gradually transform and abstract from their local application serving the child in the discovery of new physical rules and their coordination. Finally, the prime importance that even young children ascribe to an artefact's *function* serves to structure the process of building and learning. The function of the future system organizes the activities towards its realization, serving as a meter to judge how well the solution is advancing.

The reported limitations to learning are predictable. A short-lived intervention of four sessions cannot be expected to strongly impact abilities such as the number of parallel interacting objects one can reason with, that are related to long-term maturational transformations in children's memory capacity (Case 1987).

Transfer of newly minted concepts outside of the context in which they were learned would not be anticipated either. Consolidation of the new knowledge structures is necessary for transfer (Steiner 2000), needs to be learned in multiple contexts (Bransford et al. 1999) and should be consciously incorporated into learning strategies (Salomon and Perkins 1989).

The children's inconsistency in applying the new physical rules they have learned across tasks is typical of learning processes across the ages. Such variability in performance has been widely described, such as the gesture-speech mismatch when children's gestures precede their articulations in communicating their new understandings (Alibali and Goldin-Meadow 1993). Siegler (1983) portrays children's reasoning as more homogeneous when they have little knowledge about the concepts than when they have more; and later describes transitional periods of learning as partially overlapping waves in which more and less advanced strategies are used concurrently (Siegler 1996). Chen and Siegler (2000) propose five components of strategy change in solving problems in terms of strategy discovery and change: (1) acquiring a new strategy; (2) mapping the strategy onto novel problems; (3) strengthening the new strategy; (4) refinement of choices among strategies; (5) successful execution of the new strategy. Thus, the fact that the children in this study had learned a new rule following inadequacy of a previous one does not mean that it was immediately used in all situations; the latter four components require additional use and practice before a new strategy is consolidated. This study has captured the early phase of learning new physical rules, and so their use is not yet consistent across tasks.

Among the three physical relationships explored in this study, the "height rule" was explored in more depth. The children raised and lowered the pipe-end and gradually came to predict that lowering the pipe-end increased the issuing stream's flow. However, a scientific understanding of the height of water in the system takes a wider view. This view includes the water reservoir's height as a primary "mover"; its height towering over a particular exit represents the potential energy at this point: the taller the tower the greater the flow. At equilibrium the water in a system of pipes fills the vessels all the way up to a common horizontal level. This study indicates no learning of these global coordinated views among the children who had built the water systems. Analysis of the children's explanations shows three ways of explaining the flow of water. The first most common one sees no gravitational or energy restrictions on flow. As long as there's a pipe, the water will flow along, even higher than the reservoir, out of a system of pipes at equilibrium leaving no water behind; correspondingly, Brophy and Alleman (2003) have found that children across a wide range of ages were unaware that water had to be pressurized to flow. The children focus on the water's path, ignoring the system's frame of reference (the reservoir) and the earth's frame of reference (gravity). A second view entertains the earth frame of reference, sees water as flowing through pipes but places a severe restriction: water cannot go up, not at all; Piaget (1956) and Ackerman (1991) have identified similar understandings. A third view coordinates the path of flow, the reservoir's height and the levels of water in connected vessels and is least frequent among the children in the study. While the children in the study have learned a local rule that works well with variations to pipe-ends, they are far from a global understanding that generalizes and coordinates the relations across the system. As many high school and undergraduate students find these ideas problematic (Engel Clough and Driver 1985; Besson 2004), this result is expected. Together with the finding that the children do not apply their new understandings outside of the context of building, one may conclude that the children's learning through building is local in two senses: it applies to the specific parts of the system they had *manipulated*; and it is embedded in the particular *construction set*. This kind of learning has been described by Claude Levi-Strauss (1966) as the "science of the concrete", or bricolage. He uses the term "bricolage" to illustrate how people develop and assimilate ideas by using the objects around them, repeatedly arranging and negotiating with a given set of materials and not going beyond them.

One last finding is the increasing bias among both experimental and control group children towards particular system features. At the outset, all variations in the system were viewed as impacting the water flow. However, in the posttest, many children, especially the control group children ignore resistance variations as a causal factor, instead assigning greater causal status to the size of the exit-hole. This finding has been elucidated through an investigation of the experimental group's intermediate sessions and will be presented in a future paper. As will be shown, this bias describes an early phase in the children's learning progression, during which their reasoning becomes more consistent. It becomes more consistent within the children's current cognitive abilities, by focusing on one single causal feature in the system, ignoring all others. The builders eventually decrease this bias (and consistency) in favour of multiple inconsistent rules, then partly shifting to reasoning with dual variations. The study's design controlled for effects of testing, showing that this biased phase results from the discussions with the interviewer rather than from building.

The findings section reports that some of the control group children approached their parents and the interviewer on the topic of water flow following the pretest. Moreover, the transfer task showed their greater understanding of the height rule in familiar settings (albeit less than the builder's understanding of this rule in the building setting). These discussions resulted in the children's communicating, thinking and possibly exploring the topic of these interviews outside of the experimental setting, in essence embarking upon a process of learning. These findings suggest and point to the value and role of communication among peers and with adults in educational settings in a more comprehensive educational intervention.

Limitations to this study are the small sample size and several interviewer interventions. The children were interviewed about their understandings throughout the experimental period. The effect of these interventions is partially offset by the pretest and posttest interviews and the activities with a control group, as well as the fact that no feedback was provided to the children's communications—not verbally nor by using the system to demonstrate its behaviour. Arguably, these interviews provided the children with an opportunity to express and explain their understanding, a strategy that has been shown to advance learning (Chi et al. 1994).

In conclusion, this study identified young children's considerable learning through building and found some interesting aspects related to this learning, such as its local nature and the budding coordination of multiple rules. These findings show how constructing working devices importantly impacts young children's conceptual learning of science and supports intellectual growth beyond current developmental bounds.

Implications for educational settings

This experiment did not take place in a classroom. The children built and interacted with an adult individually. Generalizing from this small sample and "laboratory" setting to classrooms is not trivial. However, it is believed that the study does contribute towards an understanding of the opportunities presented by such rich design-based learning environments in early childhood educational settings. These settings frequently include construction kits and children devote themselves easily to such activities. The study indicates that in the process of building children learn the related science principles. The local "bricolage" nature of this learning suggests that additional dimensions need to be included in the learning environment. It was found that two dimensions: (1) the construction and operation of a variety of systems together with (2) encouraging children's descriptions and explanations in verbal and graphical forms supported causal learning of the related domain, understanding that was captured in the local context. Based on research into transfer of learning it is proposed that three dimensions could enhance such learning. One is longer exposure to the particular construction system so that their understanding can go through a process of consolidation (Steiner 2000; Chen and Siegler 2000). Second, an adult's interventions and scaffolding would be important in extending this learning (e.g. mindful abstraction, Salomon and Perkins 1989). Third, incorporating collaboration with other children could result in the children's ability to communicate and generalize their newly-minted knowledge to additional settings (Hatano and Greeno 1999; Campione et al. 1995). Further research into learning environments that include one or more of these dimensions could afford a comparison with the current research and an extraction of the particular features of the environment that contribute to various components of learning.

In the domain of educational design, it is proposed that the creation of engaging construction systems that are based on powerful ideas that are not tapped onto in current preschool construction sets could serve to develop early understanding of science.

Further research is needed to explore the unique contribution of construction among older and younger children and with a larger variety of topics in science. Additional exploration of how children's understanding of water flow changes with age is proposed as well.

Concluding words

The paper began and now concludes with Piaget's words towards the end of his book on the child's understanding of causality, with which he highlights the importance of action on objects in forming multiple relationships that build up to later discovery and learning: "In short, before law can be discovered and consequent correct generalizations be made, action must have woven a network of relations between the objects of knowledge" (Piaget 1956, p. 300).

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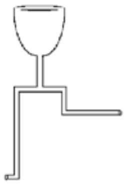
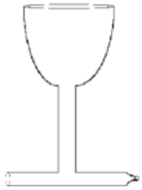
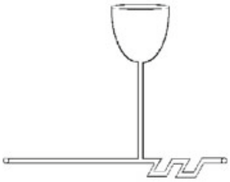
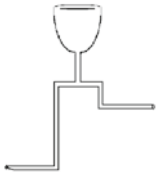
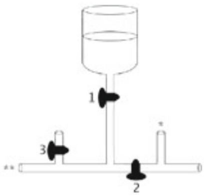
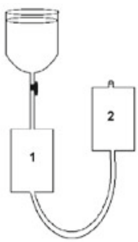
Appendix: Example questions from pretest and posttest

The following table demonstrates some of the systems used in the pretest and posttest items. The full protocol is described in the "Methods" section.

Height variation 	Hole variation. 
Resistance variation 	Height and Resistance variation 
Hole and Resistance variation 	Height and Hole variation 
Branching pipes 	Watering a high plant 
Connected vessels 	

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