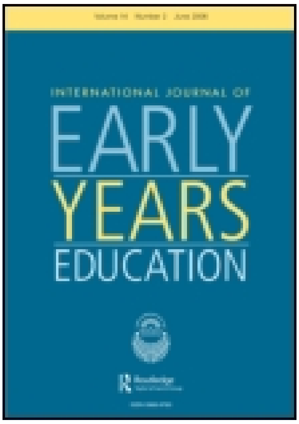

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Didactic objects for development of young children's combinatorial experimentation and causal-experimental thought

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CONTENTS

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Didactic objects for development of young children's combinatorial experimentation and causal-experimental thought

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Combinatorial abilities are fundamental to experimental thinking. The aim of this work was to design didactic objects that will stimulate preschoolers' experimental thinking and to study young children's thinking in relation to these objects. Six heuristic rules for the design of didactic objects are specified, and the responses of 623 children aged between 3 and 7 to the didactic objects are described in this paper. The first two calculating devices required rods to be pressed simultaneously for successive windows to be lit up or made visible. A total of 30 five year olds played with these for 20 minutes, and were seen to perform a logical series of actions in order to understand the device's function. Half of the children counted the presses and thereby understood the way the device functioned. The second device was designed to allow all possible combinations of four variables. Sixty children between the ages of 4 and 6 played with the device for 20 minutes. A total of 88% of the children found all possible combinations of the device, with no differences between age groups in the strategies used. The third device had a matrix of shutters opened by buttons arrayed along two edges. In the first mode, single buttons presses opened the nearest windows and button presses along both edges opened windows on coordinates determined by the two buttons. In the second mode, single button presses opened nothing and simultaneous button presses along two edges opened windows on coordinates determined by the two buttons. Ninety children between the ages of 5 and 10 played with the device in the second mode for 20 minutes. The children used scientific strategies to discover the device's function in the following proportions: 20% at five years, 50% at six years and 93% at 10 years. Eighteen children between the ages of 4 and 6 played with the device in the second mode. They played in pairs, and each child was assigned a row of buttons, thus requiring co-operation to open the windows requiring two coordinated button presses. All the children were eventually successful in the joint experimentation. The fourth device had 16 windows and eight buttons, which lit up the windows when pressed in logical combinations. A total of 20 five-year-old children were trained on this device to use combinations of button presses to light up selected windows. These children were then allowed to explore the third device in second mode by themselves. The trained five year olds all used scientific strategies in their search for the third device's combinations. The study showed that preschoolers can combine actions and discover hidden relationships, and that the didactic objects can be used to develop children's thinking.

Keywords: combinatorial experimentation; causal-experimental thought; teaching; zone of proximal development; preschool children

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Introduction

In what measure can young children explore and understand complex multivariable dynamical environments? This question is important, because the development of abilities for coping with such environments is considered a crucial aspect of human cognitive development. Presumably such abilities are also highly relevant for children's future participation in complex society. Educators try to design systems of education, that develop these abilities, which include combinatorial skills, reasoning in causal nets as opposed to causal chains, predicting non-linear dynamics and the ability to build optimal strategies of control (Demetriou *et al*. 1993; Dörner 1997; Frensch and Funke 1995; Spector 2005; Voss 2006).

The main function of causal-experimental thought is to understand the interacting structures of our complex reality by experimentation. Combinatorial abilities are the cornerstone of this specialised system, which also includes the ability to form complex hypotheses about interactions and causal connections between elements (variables); experimentation abilities (abilities to design experiments for testing the hypotheses) and the ability to construct interpretative models (Demetriou et al. 1993).

The best cultural tools for education in areas of multivariate relations are complex didactic objects. They simulate and demonstrate active intelligent functioning, including simulation of situations of physical, biological and social multivariable net determination and self-determination. Children can experiment with such an object by themselves, revealing multiple causal relations and creating virtual microworlds (Schauble and Glaser 1990).

In more general terms, objects designed to develop children's independent exploration and learning of by stimulating problem-solving skills contain some didactic programs in implicit form. These programs are revealed during a child's interaction with such an object. The structure and functioning of these objects stimulate an increase in:

(1) the variety and complexity of the child's exploratory actions with regard to the object in question;
(2) richer knowledge about it (Poddiakov 1995).

Such didactic objects are a means to reveal and control the zone of children's proximal development. In some sense, these objects are substitutes for an adult, helping the child to learn and master some activity independently. Social interaction between the child and the adult is realised in the condition of the adult's absence with a cultural tool (designed by the adult) as a substitute. Thus, these objects are a means of dialogue between the cultures of adults and children.

According to Piaget (Flavell, Miller, and Miller 2002), preschoolers (i.e. preoperational children) do not have well-expressed combinatorial skills, nor the ability to comprehend multivariable relationships. They can explore and comprehend only the simplest situations of clearly apparent interaction between two variables with two levels (i.e. not more complex situations than 2×2) (Demetriou et al. 1993). Yet Bruner wrote: 'one can indeed imagine kindergarten games designed to make children more actively alert to how things affect or are connected with each other – a kind of introduction to the idea of multiple determination of events in the physical and the social world' (Bruner 1966, 27).

The aims of my work were as follows:

(1) To formulate heuristic rules for the design of didactic objects to stimulate preschoolers' combinatorial experimentation and causal-experimental thought.
(2) The study of preschoolers' cognitive activity (exploratory learning) towards the objects, and their abilities with regard to combinatorial experimentation.

The study was conducted over 16 years (Poddiakov 2006). A collection of didactic objects has been designed. The objects are complex, having many connections and interactions between their elements. They require complex combined (for example simultaneous) actions on their controls. These combined actions cause the object to react in a way which is considerably different its reactions to a single action. A total of 623 children of three to seven years old participated in the study.

Heuristic rules[1] for the objects' design, descriptions of some of the objects, and experiments studying children's experimentation ('experimentation with experimentation') are presented below.

Heuristic rules for design of multivariable objects for preschoolers

One can formulate the following heuristic rules to design a system of multivariable objects to stimulate children's combinatorial and causal-experimental thought.

(1) The objects should contain implicit information on at least three kinds of the adults' ideas:
    (a) ideas about multivariable relations and scientific experimentation with them;
    (b) ideas about children's cognitive abilities, potentials and interests;
    (c) ideas about aims of the dialogue concerning, on the one hand, the development of children's abilities and, on the other hand, elaboration of all three kinds of the adults' ideas.
(2) Any of the objects should give children an opportunity to raise various problems, i.e. problems, differentiation in aims, methods of their achievement, levels of complexity, etc.
(3) The system should include objects with compositions of subsystems of two types:
    (a) a subsystem with one-to-one relations and without interactions of variables;
    (b) a subsystem with interactions of variables and not one-to-one relations. Representation of subsystems of both types, in varying compositions, promotes deeper comprehension of the multivariable objects and relations contained in the objects.
(4) The system should include objects that differ in a level of objectification of the following parameters:
    (a) possible variables;
    (b) their combinations;
    (c) processes of the interactions of variables;
    (d) results of the interactions.

These parameters can be clear or hidden, vary from a level of observable mechanical elements and their interactions to a level of variables and interactions that are given in a conventional verbal or symbolic way only (e.g. as a mathematical or logical rule), etc.

(5) The simplest objects should be based on content well-known to children. They should include the minimum number of interacting variables and the simplest dependencies, characterising the interactions.
(6) The following objects promote the development of children's activity on combining variables and exploration of their interaction. The objects react to single actions by effects that are considered incomplete by the children. Combined actions cause an object's reactions that are considerably different from the effects of the single actions. This means that the effects of the single actions are integrated into systems of visible interactions. As a child increases the variety of combined actions, the object reveals progressively more features. These allow the child to make progress in comprehending the object.

These heuristic rules do not pretend to be complete and universal. The system of objects, designed according to these rules, is open. That is, one can bring new objects and withdraw or modify old ones, depending on whether the aims are research and practical.

Some of the objects and the children's activity with them are described below. Equal numbers of girls and boys were selected.

The Calculating Devices

Description of the Calculating Devices

The first Calculating Device has three rods and one window with a picture behind a shutter (Figure 1a). When any of the rods are pressed simultaneously the shutter goes up making either 1/3, 2/3 or all of the window area visible. Even three year olds understand that increasing the number of the pressed rods results in an increase in the visible area of the window. This object is the simplest and can be used as an introduction.

The second Calculating Device works on the same principle, but is more complex (Figure 1b). It has a row of six rods and a row of six dark windows with obscured

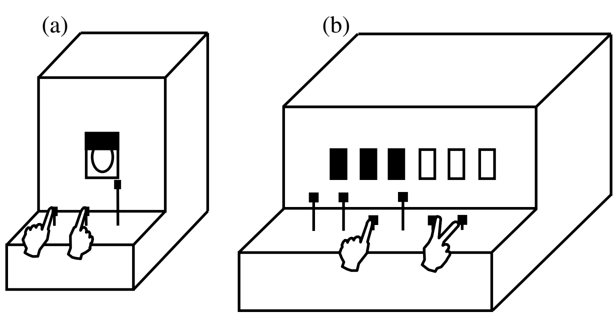

Figure 1. (a) Calculating Device-1; and (b) Calculating Device-2.

pictures of characters from popular stories. Pressing the rods lights up the windows and makes the pictures visible. Those windows that are lit up depends on the number of rods pressed rather than on their location. The device can work on two modes of this general relationship. In the 'Addition' mode, a simultaneous press of any number of rods results in the same number of windows to the left lighting up. For example, if any one rod is pressed, the first window on the left lights up, and if any two rods are pressed both the first and the second windows on the left light up, and so on. In the 'Subtraction' mode a simultaneous press of any rods will make that number of windows subtracted from seven on the right light up.

An experiment with Calculating Device-2 in 'Addition' mode

Participants

Thirty children aged five years (15 boys and 15 girls).

Procedure

Initially children played with the toy by themselves. The adult then suggested a number of tasks focused on causal relationships in the toy and possible actions on it. Namely, the child had to: (1) light up the windows shown by the experimenter; and (2) show the windows which would be illuminated if one pressed the rods shown by the experimenter.

Children were observed singly and the maximum length of observation was 20 minutes.

Results and discussion

After the first combined pressing and the object's new reaction (i.e. lighting of several windows) the children began to press other rods simultaneously. They found new combinations at an accelerated rate. The average intervals between the first pressing of one kind and the first pressing of the next kind were as follows:

(1) 18.3 pressings between the first pressing of one and two rods;
(2) 4.9 pressings between the first pressing of two and three rods;
(3) 0.9 pressings between the first pressing of three and four rods;
(4) 0.8 pressings between the first pressing of four and six rods;
(5) 1.1 pressings between the first pressing of six and five rods.

As a rule, children pressed five rods after they had pressed six rods (!)

Some preschoolers performed a logical series of actions. In these, the number of pressed buttons remained constant, but their location varied. Half the children (15) counted the pressed rods and the lit up windows. This counting allowed them to understand the way the toy functioned. At various levels of understanding, the preschoolers revealed the mathematical relationship characterised by an interaction of several factors. The children understood that this interaction could be interpreted as an effect of one complex factor – the number of pressed rods.

The Triangle Device

Description of the Triangle Device

The device is designed to give children an opportunity to see and perform all the possible combinations of four variables. This type of combinatorial thinking was previously considered only available to adolescents, and not to preschoolers (Demetriou et al. 1993; Flavell, Miller, and Miller 2002).

The device has three buttons in the angles of the bottom triangle (see Figure 2). There are two triangular windows (near and distant), with circles in the angles, above the buttons. The windows contain pictures, which become visible when the windows light up. There is a toggle switch between the windows. Its position determines which of the windows, is lit up.

Pressing any single button lights up a picture in the corresponding circle of the window. Pressing the left button lights up the left circle, pressing the right button lights up the right circle and pressing the top button lights up the top circle. Simultaneously pressing any two buttons lights up the line connecting the circles, and not the circles themselves. Simultaneously pressing all the three buttons lights up a triangle inside the window, but the circles and lines remain dark.

The pictures form a system, based on the following principle. Each circle in the window contains a picture of an object. Each line connecting two circles contains a combination of both objects from these circles. The triangle inside the window contains combinations of all the three objects.

The device is a multi-relational object that can be in 16 states. One of these is the initial state. The remainder can be set by 15 different single and combined actions, i.e. by a complete combinatorial search of four controlling elements.

An experiment with the Triangle Device

Participants

Sixty children (20 children four years of age, 20 children five years of age, and 20 children six years of age).

Procedure

The procedure was the same as the experiment with Calculating Device-2.

Results

A total of 85% of the four-year-old children, 95% of the five-year-old children, and 85% of the six-year-old children found all 15 possible states of the object. That is, they performed all the combinations of actions on the buttons and saw all the pictures. The number of actions varied between 25 (made by a girl aged six years) and 262 (made by a girl aged four years). The average was 103.5 actions. This was much more than the minimum 15 necessary actions and it should be noted that the experimenter did not make any attempt to decrease the number of actions. In a computer simulation of random actions on the controls there were 57.3 actions on average over 1000 trials. Although the children made more actions than the computer program, their actions were not random. At the beginning the children pressed

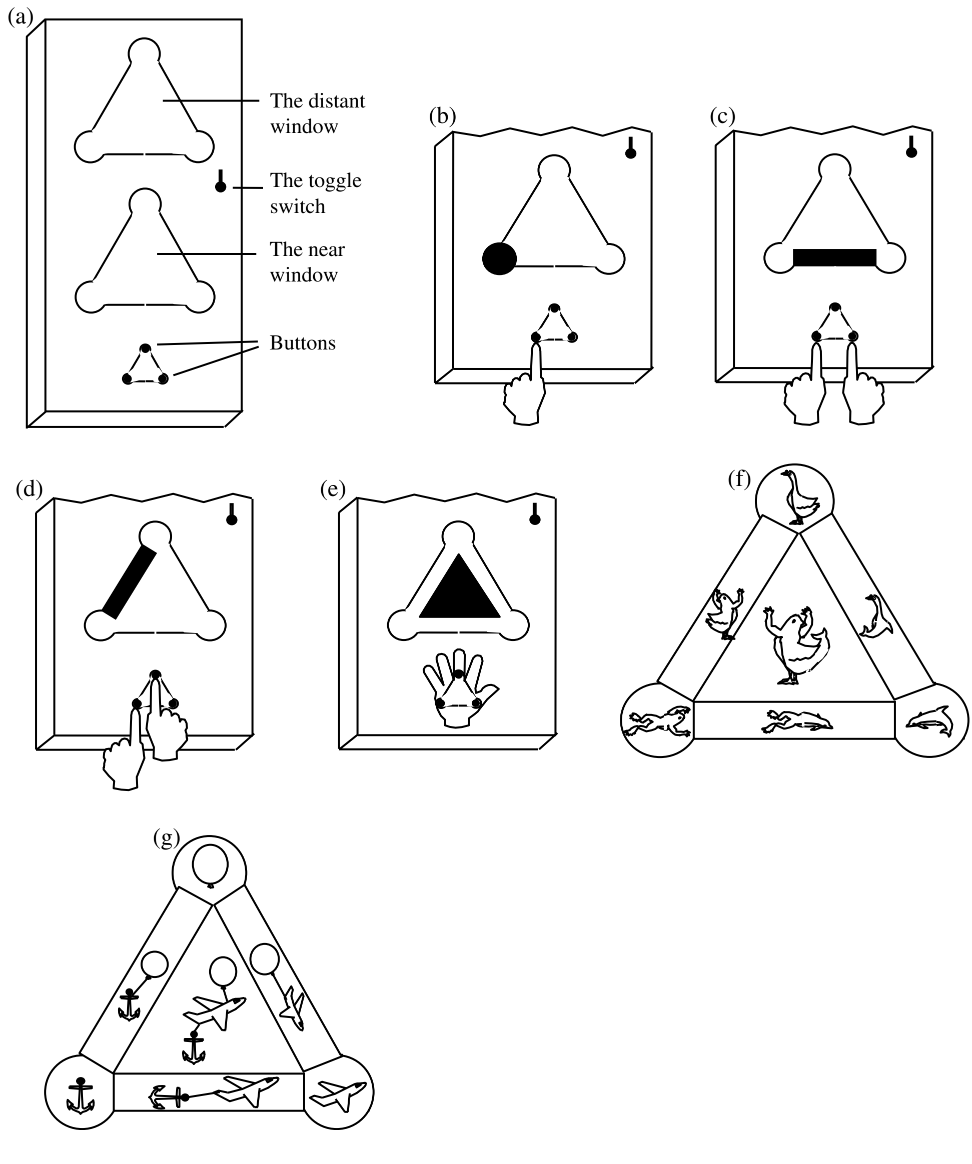

Figure 2. The 'Triangle Device' stimulating children to perform complete combinatorial search for four control variables: (a) overall view; (b) lighting up one circle; (c) lighting up a single line; (d) lighting up a single line; (e) lighting up the centre of the triangle; (f) pictures in the near window; and (g) pictures in the distant window.

buttons one by one, then they began to press pairs of buttons, and after that they pressed all three buttons. The probability of the strategies of all the participants having this similarity was < 0.0000005%. Also the children did not make inadequate actions, like pulling an electric wire, knocking on the device, etc., which one could expect, for example, from the younger children. If one enters the possibility of several such actions into the program, it will make many more actions before the end of the search because of combinatorial explosion.

Our conclusion was that all the children, even those only four years old, could find and perform all the combinations of four variables – not in the shortest possible logical sequence, but by using those strategies, that were accessible to them.

The Matrix Device

Description of the Matrix Device

The Matrix Device (Figure 3) has a row of five buttons along the bottom line and another five buttons along the left side of the box. There is also a matrix of square windows covered with flaps. These can be opened by pressing the buttons.

In the mode '*Story characters*', 35 windows (a matrix of $6 \times 6 - 1$) contain pictures of characters from folk tales. When any button is pressed, the window closest to the button opens. When two or more buttons in both rows are simultaneously pressed, windows with coordinates determined by the pressed buttons open (Figure 3a–c).

In the mode '*Shape* $\times$ *colour multiplication*', there are 25 square windows integrated into a 5×5 matrix (Figure 3d). There are five square labels with pictures of geometric forms between the buttons of the horizontal row and the windows of the

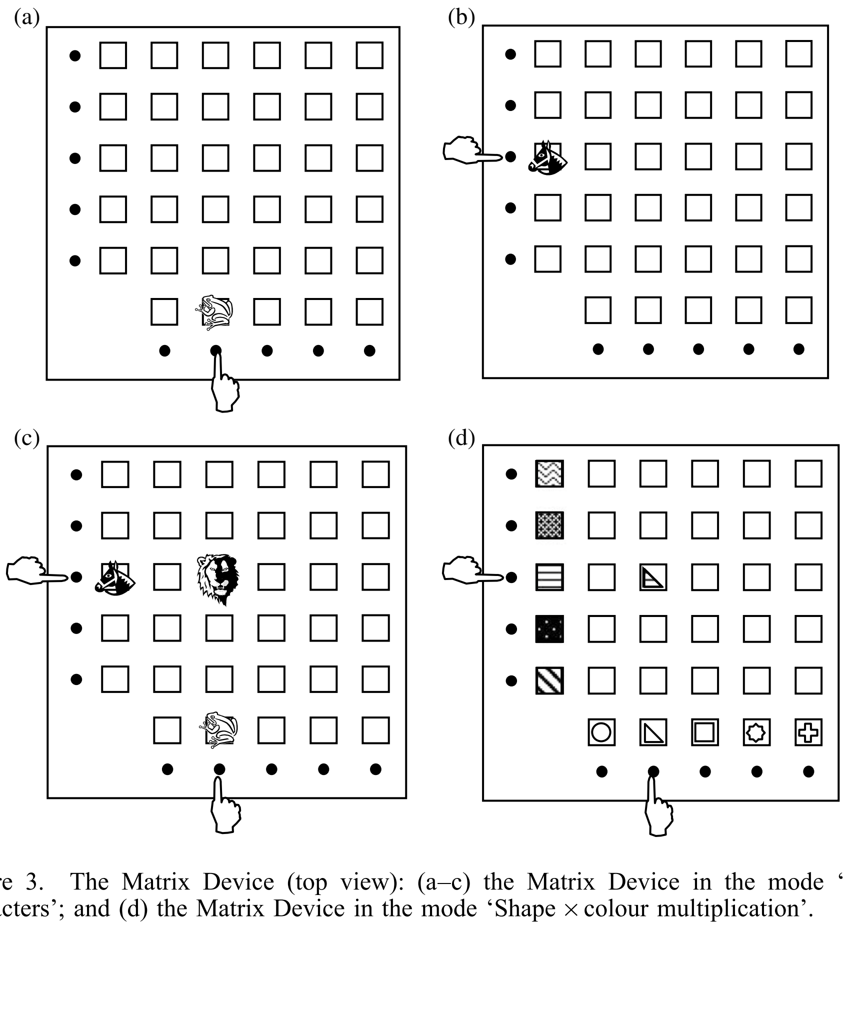

Figure 3. The Matrix Device (top view): (a–c) the Matrix Device in the mode 'Story characters'; and (d) the Matrix Device in the mode 'Shape $\times$ colour multiplication'.

bottom line, and five coloured square labels between the buttons of the vertical row and the windows of the left column. In the windows there are pictures of figures of corresponding shapes and colours. The pictures are concealed behind shutters and can be opened only by simultaneously pressing the buttons. In this mode, no pictures can be made to appear by pressing buttons in one row only.

A child's individual experimentation with the Matrix Device

Mode

'Shape × colour multiplication'.

Participants

Ninety children (30 five-year-old children, 30 six-year-old children, and 30 nine- to 10-year-old children).

Procedure

The procedure was the same as the experiment with Calculating Device-2.

Results

Six five-year-old children (20%), 15 six-year-old children (50%), and 28 nine- to 10-year-old children (93%) made an ordered search for pairs of buttons, moving in the rows in succession. This class of strategies included a sufficiently exact variant of the odometer strategy (*cf.* English 1993) in which minor items were buttons of one row (e.g. the horizontal row) and major items were buttons of the other row (e.g. the vertical row). Thus, the children used one of the *main scientific principles of experimentation*, i.e. *varying one variable while keeping the others constant*. Only those children who had used these strategies showed a high level of comprehension of the object functioning while performing tasks (Poddiakov 1994).

Children's joint experimentation with the Matrix Device

Mode

'Story characters'.

Participants

Eighteen children (eight four-year-old children, four five-year-old children and six six-year-old children).

Procedure

The experimenter suggested that a pair of children play with the new toy on their own. He told them that there is only one rule in the game: one row of buttons was for one child, the other row of buttons was for the other child and the children cannot press the other one's buttons.

Results

In the first stage the children acted independently of each other. They pressed buttons and looked at the pictures in the white windows. The second stage began when both children accidentally pressed their buttons simultaneously and noticed a picture in a new open window. Usually each of the children thought that this effect was caused by their own actions. Some children said: 'I have opened the window'. Some of their partners agreed with this. Yet others began to solve the question as to which of them had in fact opened 'problem' windows. For example, P. Seva (6;6) said: 'I have opened a picture of Red Hat'. M. Misha (6;9) answered: 'No, it is I who has opened Red Hat'. They began to argue angrily: 'It is my Red Hat!', 'No, mine!', etc. But all of a sudden Seva found a way to show that he was right. He withheld his button and said: 'But I have closed your Red Hat'. This was a very important moment. The child proved that he was a participant of the device control in equal rights by using not positive, but negative information (i.e. information about the button withheld and the window closed). Usually children figure out 'authorship', for example, in playing joint computer games, by making more frequent and intensive actions, not by stopping them (Forman 1986). Yet our object stimulated children to invent a more advanced strategy. After that the children performed several pressings and withholdings and understood that opening of the pictures was a result of their joint and simultaneously performed manipulations ('We have done it together'). In the third stage of activity these children began to coordinate their aims and actions, talking with each other in a very polite way. (This transition from the mutual anger to the politeness was rather amusing.) Yet such kind of interaction characterised by the children's clear discussion of their viewpoints was observed rarely, that is two times of nine. It was demonstrated by one pair of five-year-old children and one pair of six-year-old children. Usually partners did not speak about their view points so clearly. (I think the discussion can be stimulated by the experimenter's remark: 'O-o, I see the window gets open. Who has opened it?' But, unfortunately, it had occurred after the experiment.)

Thus, the experiment has shown that joint experimentation and discussion can stimulate successful understanding of the multivariable object in some children at this age.

The Multiplication Device

Description of the Multiplication Device

The Multiplication Device realises non-matrix 'shape × colour' logical multiplication (Figure 4). The device has two rows of buttons located in a straight line. Each of the rows has four buttons. There are coloured labels opposite the buttons of one row and labels with pictures of geometric forms opposite the buttons of the other row. The device also has 16 little round windows with electric lamps. The windows are grouped into four clusters, each of the clusters containing four windows. Each of the windows is characterised by two features. These are the colour of the lamp and the shape circumscribed around the window. To light up a window one has to simultaneously press two buttons, one of which has a label of the same colour and the other a label with the same shape. The technical properties of the device allow the experimenter to exchange positions of shapes round the windows, as well as

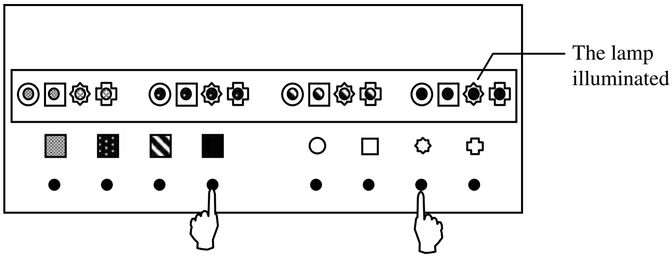

Figure 4. The Multiplication Device (top view).

positions of the labels, and vary connections between the buttons and lamps thus producing different variants based on the general multiplication principle.

An experiment: transfer from the Multiplication Device to the Matrix Device and creating new knowledge

The Multiplication Device was used for training children and study of opportunities of the knowledge transfer to subsequent independent exploration of the Matrix Device. We supposed the trained children should be able to successfully explore the Matrix Device as a whole and, most importantly, to comprehend the subsystem which was not included in the content of the training (i.e. the subsystem of spatial relations of rectangular coordinates that was absent in the Multiplication Device).

Participants

Twenty five-year-old children.

Procedure

The study was conducted in two stages. In the first stage the experimenter taught the children to use some techniques of combining actions and comprehending relations in the Multiplication Device (for more details see Poddiakov [1992]). At the second stage of the study the children explored the Matrix Device by themselves.

Results

For various subsystems of the Matrix Device, between 12 and 16 trained children (i.e. between 60% and 80%) showed a high level of control of the subsystems, including the subsystem of spatial relations that *was not presented in content of the previous teaching*. Only one of 20 non-trained five year olds showed a similar result. All the trained children performed the strategies of ordered combinatorial search that they learned while training, in particular, strategies of varying one button and keeping the other button constant. Only four non-trained children did so. (Differences between the trained and non-trained groups were significant at $p < 0.01$.) Thus, during independent experimentation on the novel multivariable object five-year-old children could successfully transform the system of knowledge which had been given to them by the adult in the course of the training. They transformed it into such a new system of knowledge that was adequate to the novel object and that was not in the content of the training.

Conclusion

(1) Combinatorial (multivariable) experimentation aimed at exploration of multiple interactions in complex objects is a special, earlier unknown or at least underestimated direction of young children's cognitive development. This activity can be very interesting for the children and serve as a precondition for development of initial forms of system thought.
(2) Most preschoolers can successfully combine actions, comprehend and use various multivariable objects containing hidden mechanical, logical and mathematical relationships (up to six variables), though their combinatorial strategies are not general and logically exact (are not at formal operational level, in Piaget's terms).
(3) The didactic objects can be considered as a way to reveal and control the zone of a child's proximal development, in Vygotskian terms. They are substitutes for an adult, helping the child to learn some activity independently. These objects are a means of dialogue between the cultures of adults and children: they reflect adults' ideas about multivariable relations and scientific experimentation with them, ideas about children's cognitive potentials and interests, and ideas about aims of the developing dialogue itself.

Discussion

A purpose of the toys described in this article is to stimulate children's interest, provoke them to 'ask questions' about these objects, invent and test different hypotheses, elaborating their knowledge and competences. Experimenting on such objects, young children reach higher levels of cognitive achievements related to the development of causal thought and understanding of multifactor interactions, logical, physical and mathematical relationships.

In general, results of the experiments with the multivariable objects of our collection (including some other objects and games not described here) allow us to speculate about the following possibility. What would it be like if children from early years could regularly interact with the objects introducing a child into – let me quote J. Bruner again – 'the idea of multiple determination of events in the physical and the social world', and these objects would become relatively mass phenomenon, a part of everyday culture?

We cannot know any exact answer to this question, but one may take into account here results of studies conducted by Chen and Klahr (2008). They have studied effects of culturally specific experience on long-term transfer, and shown that Chinese and the US college students are better at solving logical and mathematical problems that are isomorphic with problems based on European vs. Chinese folk tales heard many years ago, in their childhood, than other problems. Also some positive effects of children's experimental learning to solve multivariable problems on their solving isomorphic problems in a few months and one year have been found, but these effects were not significant in the same degree in two-year-delay posttests (Ibid.).

Again, what would it be like if multivariable objects demonstrating opportunities of multivariate actions and multiple determinations were available for children on a mass scale? Even a few decades ago such ideas were very difficult to realise because of technological limitations. (I was making my first object for three months using elements from electrical and mechanical toys and Meccanos. Making its copy would take almost the same time.) Recently new chorded keyboards of variable geometry can be based on well-elaborated multi-touch technologies built in such toys.

Has our culture aspiration to introduce children into ideas of multiple determination in mass scale, and not only at the level of single psychological and educational experiments? If yes, we will perhaps see unexpected results from this cultural and educational constructivist activity.

Acknowledgements

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Note

1. The 'rules of thumb' that increase the likelihood of solving a problem.

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