Make or Shake: An Empirical Study of the Value of Making in Learning about Computing Technology

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ABSTRACT
Learning about computing technology has become an increasingly important part of the school curriculum but it remains unclear how best to teach it to children. Here, we report on an empirical study that investigated how the process of making affects how children of different ages learn about computing technology. In one condition, they had to first make an electronic cube before conducting other activities and in the other they were given a ready made one to use. The results of the study show that for younger children, the making significantly improved their performance in a post-lesson test, whereas the older children performed equally well in both conditions. We discuss possible reasons for this, in terms of differences in creative appropriation. We also saw much spontaneous collaboration between the children that suggests making can encourage a collaborative relationship between children of different ages.

Author Keywords
Making; Learning; Active Learning; Electronics Kits; Preparation for Future Learning.

ACM Classification Keywords
K.3.2 Computer and Information Science Education, H.5.2 User Interfaces

INTRODUCTION
Learning about computing technology is becoming an increasingly pervasive part of children's early education. In the UK, for example, the national curriculum has recently been changed so that children will start to learn about computing technology from as young as 5 years old [14]. This mirrors a global trend to integrate learning about computing and information technology into young children's education. By *computing technology* is meant learning about computing concepts in a broad sense, with or without traditional computers, e.g. with robotic platforms such as Logo Turtle Robots [27] or Bee-bots [40].

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Figure 1. (left) MakeMe, (center) making the cube, and (right) exploring sensors and lights through shaking.

However, educators are still divided as to how best to teach children about computing technology to achieve a positive attitude towards the subject, spark curiosity and begin developing the understanding and problem solving skills that will set children up for learning throughout their school career and beyond. Our research is concerned with contributing to this debate by providing empirical evidence about the benefits of including *making* as part of the new curriculum about computing technology. In particular, whether the tactile, physical process of making can enhance learning, as well as the much publicised benefits more generally of 'making' as a creative process.

Outside of school, Kafai and Burke [22] describe a *"social turn"* which is taking place among children learning to code informally online with visual programming languages such as Scratch. Rather than simply learning how to code as individuals they are taking part in *"computational participation"* [22] based around online collaboration and communities. In this case applications are made to share with an online audience and code is constantly being reused and remixed by different collaborators. Kafai and Burke challenge educators to bring this same sense of enthusiasm in participation and collaboration into the classroom. One way could be to introduce children to computing technology through physical construction as well as on traditional computers.

There are a whole host of kits and toys (e.g. [5,9,13,23]) that can make computational thinking physical by enabling children to creatively build their own interactive devices. These reconfigurable construction kits are understood to enhance learning by enabling children to creatively construct physical artefacts that represent underlying ideas about how things work [2,27,28]. However, it is less clear if the physical act of construction enhances learning, even without the option for creative reconfiguration. This paper aims to address this gap in knowledge by addressing the following research question:

Does the constructing of a device enhance learning? If so, how?

One theory that is particularly relevant to this question is *Preparation for Future Learning (PFL)* [10,37]. This theory argues that previous experience prepares children for learning new things by providing concepts and schemas that they can apply to different situations. Physical and tactile objects can be particularly useful for forming schemas in primary age children [25]. We propose that actively involving children in making computing technology themselves can help them to form schemas such as input-processor-output and prepare them for learning about how computing technology works.

To this end, we designed an electronics kit – called MakeMe – that allows children to explore an interactive sensing cube that uses sensed motion gestures to illuminate the cube in different colours (Figure 1). To determine whether adding making to the mix enhances learning we tested two conditions. In one condition, young children learned about sensors and processors by building a MakeMe cube from the kit and then carrying out a number of exploratory activities to find out how it works. In the other condition, children were given the cubes ready-made with an explanation and discussion of the components in the cube and then asked to carry out the same exploratory activities. The exploratory activities were the same in both cases and comprised shaking and gesturing with the cube to discover how input from the motion sensor controlled the output in the form of coloured lights on the MakeMe cube. The learning outcomes for the two groups were then compared to test the hypothesis that the children would learn better in the making condition. The findings showed marked differences between the two conditions. We discuss these in terms of the value of *making before doing* versus *starting off by doing*.

We begin by introducing the background of Preparation for Future Learning as well as tangible learning, making and coding approaches. Next, we introduce the MakeMe kit design, and then describe the aims and objectives of our study. After outlining the study design, we report our major findings across four aspects of learning: knowledge acquisition and age effect; engagement; creative appropriation; and collaboration. We close with a discussion of our findings.

BACKGROUND

Several educational theories suggest that making could be valuable to learning, in particular, Constructivism [30], Constructionism [27, 28] and Preparation for Future Learning [10, 37]. Constructivism and Constructionism both take the view that learning is a process where learners discover and construct knowledge for themselves. Constructivism focuses on how experiences are internalised and reflected upon by the learner to create an abstract understanding of how the world works. Constructionism advocates the value to individual learning of externally expressing ideas and feelings through creation [2] and places value on external aids or *"objects to think with"*, which are used and created by learners to better enable their learning [27 p.11]. Both theories agree that learners need to actively engage with the world to understand it. Making is one example of active learning, where, through discovering how different parts fit and function together the learner constructs a model in their mind of how the computing technology works.

Preparation for Future Learning (PFL)

Preparation for Future Learning (PFL) argues that certain activities can prepare students for learning about related subjects in the future [10,37]. For example, students who spent time preparing for a lecture by analysing data to look for patterns learned more from the lecture than students who spent the same time summarizing a textbook chapter about the same patterns [10]. The literature on PFL suggests that activities that get students to actively engage with a subject before formally learning about it are more effective for preparing students than activities that are more passive. These preparation activities are believed to aid learning by supplying concepts and schemas that students can use to *"know with"*. For example, in the case of the pattern discovery the students are sensitized to different possible patterns that could exist and how they relate to data. Research shows that tactile, physical tokens can provide students with schemas that aid future learning and that the schemas are affected by the physical properties of the tokens [25]. For example, using pie piece shaped tokens to learn about fractions enables students to progress quickly in their learning initially, but students are less innovative in their future learning because the schema is inflexible. On the other hand, students with simple square tokens progress slower initially but take on more challenging tasks because the schema is more flexible.

So far there hasn't been any research on whether the physical act of construction can prepare students for future learning. Nevertheless, this research about learning with physical objects suggests physically making a simple computing device could provide a useful schema to aid students in learning about computing technology.

Tangible Learning

One important aspect of involving making when learning about computing technology is that it is a tangible. This concrete experience can make it easier to understand how something works compared with learning about abstract concepts. The research on interactive educational tangibles [4] is concerned with creating (and evaluating [20]) more engaging and stimulating learning experiences – and possibly facilitating children's understanding of concepts taught [24]. For example, E-du Box [11] introduced a multi-modal educational authoring platform, integrating tangible companion objects to enrich the experience. For older children, Boda Blocks [12] introduced tangible, stackable cubes as representations facilitating learning about three-dimensional cellular automata. Towards actuated interfaces, Topobo introduced re-configurable and re-trainable modular robotic elements [32]. The work on Sonic Blocks [16] revealed children's unique approaches to thinking and cognition with tangibles, differing significantly to the visual interaction model. Tangible experiences are valuable to learning because the affordances and constraints of tangible artefacts can change how learners explore and solve different problems, giving learners new insights. We argue that in the case of making this is particularly so, because physical affordances can suggest ways of putting things together and the act of construction gives insight into how something functions.

Toolkits for Making

The Maker Movement [7,39] advocates the value of Making: being able to make, hack, craft and appropriate technology empowers people, inspiring them to new levels of engagement and creativity. Experiencing how different tactile materials and components work together produces a different understanding of technology compared to simply consuming it. Rapid prototyping toolkits are the enabling technologies for such experiences. Phidgets provided physical building blocks as the equivalent to graphical widgets [17], dTools [18] simplified the building of sensor-based prototypes, and Stanford's iStuff platform [8] offered a wide range of physical input/output for experimentation. More recently, successful platforms and communities like Arduino [5] and RaspberryPi [33] have made tinkering and experimenting more accessible and mainstream [38,39]. These computing technology kits invite creative exploitations of electronics and coding and it is not surprising that making activities, such as digital fabrication and using electronics have become part of school curricula (e.g., [14]). However, the entry level for using these toolkits is still very high for primary school aged children.

Low-tech, craft-inspired approaches are also emerging for working and experimenting with electronics. Perner-Wilson et al. [29] introduced the kits-of-no-parts approach, using familiar off-the-shelf craft materials for constructing handcrafted electronics which aim to send a *"friendly message to new circuit builders"* [31]. Their textile sensor designs *"afford visibility",* expose the inner workings of sensors to enable people understand the technology *"and in turn craft their own interfaces"* [29]. This idea is taken further with sketched circuit designs [31] that expose circuits as silver ink-drawn sketches on paper – including the possibility to add microcontroller interactivity [26]. Makey Makey [21,36] makes everyday materials interactive without programming, by simply connecting the objects to a sensing board that triggers keystroke events when touching the object (e.g., building a banana piano).

Creative Coding for Children

For learning about software, Resnick [34] pointed out that coding activities are not only about teaching the underpinnings of mathematical and computational logic, but should also support problem solving, coming up with creative designs, and communicating ideas. Based on this philosophy emerged the design of Scratch [36], and similar tools, empowering a generation of young children to creatively build interactive graphical software, limited only by their own imagination. What made Scratch so successful was the encapsulation of fundamental programming concepts into visual programming building blocks that were 'inviting' for children to play and experiment with. It not only lowered the threshold for getting started with programming, but also made writing software accessible and tangible. The visual building blocks remove the fear of tinkering with code and instead provide affordances for assembling logic blocks in new and creative ways.

Electronics for Children

Electronics kits have also been developed for the classroom with the aim of lowering the threshold for making and learning about electronics concepts. Resnick and Silverman discuss ten guiding design principles for construction kits for children; including the advice to choose the "black boxes" (i.e., the discrete parts that perform a function with no explanation of the internal workings) carefully, or supporting many paths and styles [35]. LittleBits [9], in particular, was designed to bridge the gap when beginning to explore electronics by facilitating the creation of new circuits with sensors and actuators, and by using small electronic components that magnetically snap together. This simplifies making because the constraints of the connectors mean that parts cannot be connected the wrong way around. The toolkit introduced the notion of electronics as a material, changing the way we approach the exploration of electronics.

A related approach, LightUP [6,13], also uses magnetic connectors to enable children to put together electronic circuits. In this case the circuits are more complex to put together but teach additional concepts about electronics. It has been designed so that the built circuit resembles a schematic circuit diagram enabling learners to make connections between the physical circuit and theory in textbooks. In addition, augmented reality enables learners the ability to use a smartphone to see how electricity flows around a circuit. This enables basic electronics concepts to be communicated through making.

These recent kinds of toolkits all emphasize the value of making and assembling in learning about computing technology. Our review also suggests that there is a strong basis in learning theory and some empirical evidence that the process of making can have a positive effect on learning. However, few studies have investigated the effect of making in the classroom compared to other forms of active learning, especially for computing technology. We report here on an experimental study conducted in-situ in a school class. To answer our research question of how assembling a device can enhance learning we compared two conditions for learning about computing technology, one involving making an electronic cube first followed by a set of activities and the other conducting a series of activities with a ready-made cube. To begin, we describe the design of the MakeMe cube.

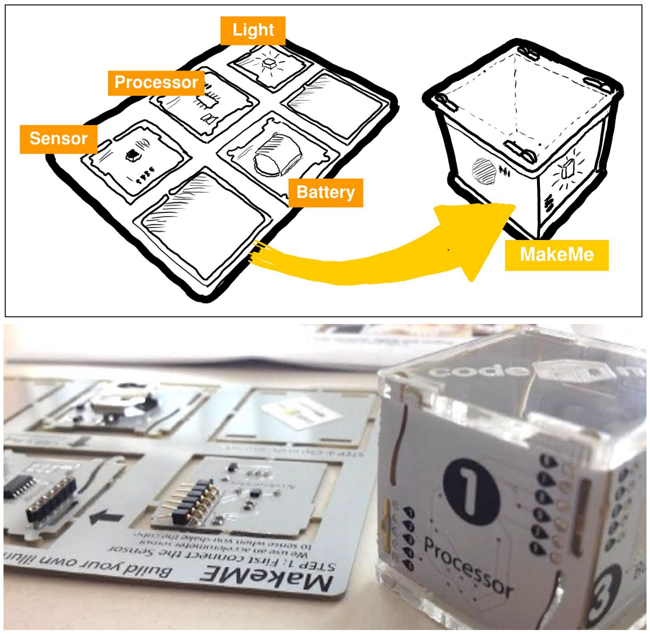

Figure 2. The MakeMe kit: (top picture) sheet with all components on the left and assembly of cube on the right, and (bottom picture) the final built MakeMe cube.

THE MAKEME CUBE

The MakeMe cube is an interactive cube (size of 4x4x4 cm, Figure 1 left and Figure 2) for learning about computing technology, designed so it can be assembled from a flat sheet, comprising six sides of the cube (Figure 2, top). Important design goals of the cube were to build a universally accessible, gender-neutral sensing/actuation device, that should support social and discovery-based explorations of electronics and coding and introduce computing concepts that are readily linked to the children's everyday worlds. MakeMe contains a sensor (accelerometer to sense motion), a processor and an actuator (colour light-emitting diode, LED) as well as a battery to provide power. Each face is designed to represent a distinct concept: sensor/input, processor, LED/output and power; the last two faces are made from clear acrylic and act as windows to see the inside of the cube. As learners connect the sides of the cube together they are able to see how the input connects to the processor and the processor connects to the output. The last step is connecting the power and the children are able to see the cube power up as the connection is made (Figure 2, top). The design differs from other toolkits by using the printed circuit board (PCB) as a material itself, where the cube is built by assembling the sides included on the board, transforming the 2D sheet into a 3D – and fully functional – sensing cube (Figure 2, bottom). The MakeMe cube is designed to teach the concepts of input, processing and output, as well as the practical knowledge about different electronics components.

The building of the cube forms a puzzle-like activity. It is supposed to achieve a balance of being challenging but not too challenging. The aim is to give the maker an opportunity to have a closer look at the various components of this interactive system and how they fit together through the process of construction. Through the process of making learners construct a tangible object through which to structure their ideas with [28].

Three MakeMe Activities

Three activities were developed for MakeMe to enable the cube's expressive features to be explored. The activities are designed to further understanding of the world of sensing and computing devices. The activities focused on 3D building and making and understanding cause and effect between an accelerometer input and changing LEDs.

1) Make: Figuring out the correct assembly of the sides from the sheet to fit together into a 6-sided cube.

2) Shake: Shaking the cube to trigger the LEDs to light up in various colours inside. The cause-effect is mapped to the intensity with which the cube is shaken: waving it slightly back and forth shows a red colour, increasing intensity of the shaking triggers first orange, then yellow, then green; and shaking it very fast causes it to flash rapidly through a series of different colours.

3) Gesture: Pulsating colour effects of the LED can be revealed when holding the cube and gesturing specific shapes in the air. For example, moving the cube in a U-shape motion causes the light to pulsate in blue, and a similar motion for the letter L causes a purple colour. The cube differentiates between the different movements along the three axes of the accelerometer, mapping the patterns of these movements to the particular colour effects.

MakeMe Pilot Study: Initial Findings

Initially, a pilot study was carried out where the cube was tested at three outreach events with small groups of children aged between 5 and 15 years to determine whether the cube could be assembled. These events showed the range of children constructing the MakeMe cube, although the younger ones found it more challenging. Another finding was that all the children had a sense of achievement after completing making the cube, as evidenced by showing the rest of the group their colour-changing cube when it started working. We also observed that the process of making the cube gave time for the children to inspect and think about how the different components in the cube fit together. This led us to hypothesize how this kind of electronics making is beneficial for learning about computing technology.

AIMS AND OBJECTIVES

The aim of our study was to test the hypothesis: *Making a device in terms of constructing it improves learning about how it works.* To operationalize making and learning we need to understand what they are and how to measure them. First we need to define making. Here we are using making to mean assembling component parts to form a physical object that has new functionality compared to the sum of its parts. Specifically, for our study the making activity comprises assembling the faces of a cube fitted with electrical components in the correct way in order to construct an interactive device.

There are different stances on what is meant by learning. Piaget takes the view that learning is the process of taking concrete experiences and forming abstract models of how the world works [30]. He suggests that as a child develops and grows older they are gradually able to understand further and higher levels of abstraction. Preparation for Future Learning [37] argues that a key aspect of learning is the ability to transfer concepts and schemas to new situations and combine these with the new information available. Another perspective is that knowledge is situated and abstracting it from its context is sometimes inappropriate [2,3]. Instead, learning should be viewed as getting a deeper understanding and connection to a particular activity in context. A fourth view, which has a pragmatic rather than a theoretical basis, and is arguably at the core of school examination systems, is that learning is the acquisition of the type of knowledge which can be measured on a written test. A further view is that collaborative learning can be highly beneficial, where pairs and groups contribute and learn from each other's resources and skills [15].

Rather than take a particular stance on learning, we chose to measure the following four aspects of learning that draw from the different definitions:

(i) **Knowledge acquisition** (as measured by a multiple-choice test)

(ii) **Engagement with learning** (as measured by a questionnaire and through observation)

(iii) **Creative appropriation** (measured through observation and discussion with the children)

(iv) **Collaboration between peers** (measured through video analysis)

Knowledge acquisition measured by performance on a test is the standard way to provide a quantitative measure of what has been learned. In our test we asked questions about both concrete behaviours of the cube (e.g. which colour it turns when shaken quickly) and more abstract ideas about how the data flows from the sensor to the processor and then to the light output (this was shown visually in a diagram).

Engaging with learning is often important for deeper understanding and was found to be prevalent in the pilot study. Our objective was to investigate how much this was due to the making element of the lesson and how much it is due to other elements about the lesson, such as novel technology and an active learning teaching style.

Creative appropriation and application of knowledge demonstrates active and situated understanding of computing technology. We found it occurred in the pilot study. We chose to investigate this by observing and questioning the children about their ideas for future development of the cubes.

Collaborative learning is important for triggering reflection and discussion. This was evident in the pilot study. Here, our intention was to investigate whether making is characterized by different levels of collaboration.

The pilot study also suggested that *age* has an effect on the level of challenge that the MakeMe activities pose for the children. Piaget's stages suggest that older children find it easier to understand abstract concepts than younger children. Therefore, a further aim of this study was to take into account how the effect of age on making.

STUDY DESIGN

This study has an independent measures design with two conditions:

Condition 1 Making: the children make the cube before carrying out a set of exploratory activities

Condition 2 Ready-made: the children examine a made cube, finding all the different components on it before carrying out the same exploratory activities

Table 1 provides an overview of these conditions and the exploratory activities. In both conditions the two groups took approximately the same length of time and were taught by the same researchers, although the teachers assisting the class were different in each condition due to the exigencies of conducting a study in a school and needing to fit with their timetable. Before the study, parents were asked to sign consent forms for their children to take part.

Participants

96 children aged between 6 and 11 from two rural state run primary schools took part in the study. The primary schools were federated meaning they share the same head teacher and governors. Two classes were run at each school, with class sizes of between 20 and 30 pupils. One class from each school experienced condition 1 (making) and the other class from each school experienced condition 2 (ready-made). In order to make the study fair all classes had the same mixture of ages (6-11 years). Since there was such a wide mix of ages in each class, younger children sat next to older children to encourage peer support. This mix of children was not normally in a class together, so the younger children did not know the older children very well. The lessons each took 1 hour.

The children had already experienced some computing lessons before as part of their regular schooling which involved programming using a graphical programming tool: 2Code [1] for the younger children, Scratch [34] for the older children. They had also used Bee-Bots [40] similar to the Logo Turtle to practice some aspects of programming.

Lesson Plan

All lessons took the same format, using the same content taught by the same researchers (see Table 1). The Making/Examining section of the lesson was taught as a discussion with the researchers posing questions (e.g. "Can you find the processor?" and "What do you think a processor does?") with children putting their hands up to give ideas. Then the researchers clarified with a full explanation. In condition 2 more time was spent on these discussions than in condition 1 where the children spent a considerable amount of time assembling the cubes. The lessons in both conditions took approximately the same amount of time.

Activity	Description	
Introduction	Introducing the researchers leading the class. Explaining the experiment. Getting consent from the children to carry out the study.	
Making/-Examining	*Condition 1:* Children make MakeMe based on step-by-step instructions from the researchers.	*Condition 2:* Children have MakeMe ready-made, researchers ask them to examine each face and tell them how the components relate to one another.
Exploring	The children are challenged to work out what the sensor on MakeMe senses by experimenting with different ways of interacting with the cube. At the end, the researchers summarize what each component does and how they work together.	
Shaking	The children do a shaking activity trying to make each colour on the activity sheet by shaking it at different speeds.	
Gesturing	The children press the button with their finger and draw different gestures in the air. This will result in a corresponding colour. The children try to make each colour on the activity sheet.	
Summary	Researchers summarize the lesson, including recapping what each component does and how they work together.	
Post-tests	Children answer a short test to measure learning and a questionnaire to gauge engagement.	

Table1: Lesson plan for the two conditions.

Data Collection

At the end of the lesson, the children were asked to answer a six question multiple-choice test to measure how well they understood how the MakeMe cube worked. Two questions tested whether the children could remember which colours the cube changed to when they shook it at different speeds. The other four asked whether the children could remember what each component does and how the data flows from the sensor to the processor and then is turned to an output in the form of a light.

To measure engagement, we used a smile-o-meter of five faces from sad to happy. Four questions (see Table 3) used the smile-o-meter to measure engagement with this activity and engagement with their normal computer-based lessons for comparison; these questions are given in the results section. There were two further open-ended questions which asked them about their favourite and least favourite parts of the lesson. Some of the children were very young and found reading the questions difficult. In these cases, a teacher or older child helped by reading the questions aloud to them and in some cases also wrote down their answers.

In order to study levels of creativity and collaboration some of the lessons were also video and audio recorded. The lessons at the first school could not be video recorded due to requests from parents. In the second school the lessons in both conditions were recorded and these were used for video analysis to give a comparison between conditions. As creative appropriation is hard to predict and record, we studied this through observations noted at the time and taken down from the video. At the end of the class we carried out short impromptu interviews with groups of children about what they would like to add to the cube and how they would use it. At the second school, the interviews were videoed on a hand-held camera.

For the video analysis of collaboration, ten-minute videos were taken from each condition. In condition 1, a ten-minute sample was taken from the making activity and a ten-minute sample from the gesturing activity. In condition 2, a ten-minute video was taken from the gesturing activity only. A recording fault meant that earlier parts of this lesson were not analysable. Ten minutes was chosen because it was approximately the length of each activity and confining it to ten minutes cut out the cross over period between activities. Each ten-minute sample was split into 60 x 10 second windows. For each window the current activity of each participant in view was noted (6 or 7 participants are in view of the camera). These activities were then coded in terms of their level of collaboration. The coding scheme used was as follows:

- **Collaboration:** helping one another or carrying out activities together
- **Interaction:** conversing and showing each other their achievements
- **Partial interaction:** talking without anyone responding or watching someone without them being aware
- **Individual work:** working without any visible interaction with another person
- **Interacting with the teacher:** listening to, being instructed by or conversing with the teacher

The strength of the analysis is limited by the small number of participants that were videoed (due to the difficulties of an in-situ study). However, it does help us reveal the differences between the two conditions and all of our results are supported by the observations of the researchers at the time.

RESULTS

The overall findings from the experiment showed that making has a significant impact on learning, especially for the younger children. Below we examine in more detail the 4 aspects of learning operationalized in the hypothesis.

(i) Knowledge Acquisition and Age Effect

A two-way factor ANOVA was carried out using SPSS on the number of correct answers to examine the effect of age and condition. The results show a significant effect of condition ($F = 5.923$, $p<0.05$), age group ($F = 4.361$, $p<0.05$) and an interaction between age group and condition ($F = 8.599$, $p<0.01$). Table 2 and Figure 3 show the results for the different groups, showing that the making condition had a significant positive effect on learning for the younger children but not for the older children.

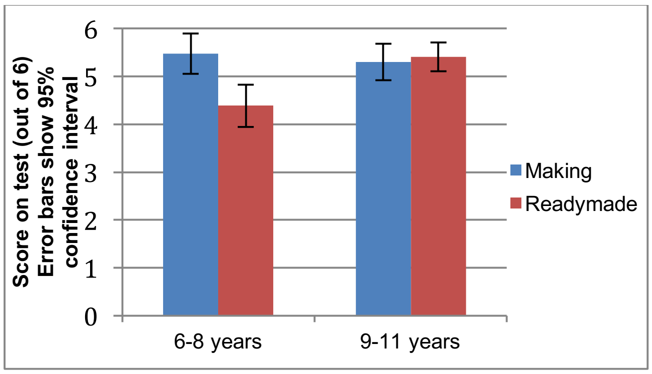

Figure 3: Mean correct answers on test for different age groups in each condition.

	6-8 years			9-11 years		
	Mean	SD	N	Mean	SD	N
Making	5.47	0.90	19	5.30	1.10	33
Ready-made	4.39	0.93	18	5.40	0.77	26
t-test result	p = 0.016			Non-significant		

Table 2: Results comparing making and ready-made conditions for each age group. N = number of participants.

(ii) Engagement

Children in both conditions found the activities engaging as evidenced by their answers for the rating scales. As Table 3 shows, they rated the lesson highly for all three questions about enjoyment with no significant differences between conditions. This was also backed up by observations in the video analysis that the children generally remained focused and engaged with the activities throughout the lesson. However, at the time both researchers observed in their notes that there was a more passive atmosphere in the ready-made condition (condition 2), this is backed up by the video evidence on collaboration which is discussed later.

It is difficult to tell from the scores of the questionnaire whether there is a difference in how enjoyable the lesson was as the ratings are all uniformly high and the independent measures design meant that the children were never able to compare the two ways of learning. However, evidence from the video analysis suggests that for some children this stood out as a particularly special lesson with comments such as *"this is the best lesson ever"* and *"this is really awesome."*

The responses to the open questions about the children's favourite and least favourite parts of the lesson revealed that 50% of them who experienced making the cube mentioned this was their favourite activity in the lesson. Whereas, only 9% said it was their least favourite activity of the lesson. This suggests that the making activity was an engaging addition to the lesson. In the condition where we gave the cubes to the children ready-made, one student asked if she could take the cube apart in order to build it.

Question	**Making (1)**	**Ready-made (2)**
1. Was this lesson boring or fun? (1 = boring, 5 = fun)	4.73	4.59
2. Would you like to do an activity like this again? (1 = not at all, 5 = very much)	4.62	4.34
3. How much do you like learning using the cube? (1 = dislike, 5 = like a lot)	4.73	4.55
4. How much do you like learning using a computer? (1 = dislike, 5 = like a lot)	4.67	4.68

Table 3: Results from the questions about engagement for each condition.

Another interesting observation noted by the researchers at the time was that many of the children who had made the cube asked if they could take it home with them. Whereas, none of the children in the ready-made condition asked this, instead they were interested in where they might buy one like it. This shows a differing sense of ownership of the cubes: the children who have made the cube want the specific one that they have made; whereas, the children who have been given the cube ready-made are happy with a generic cube.

(iii) Creative Appropriation

To measure creative appropriation we analysed the video recordings from the second school in the study for evidence of creative ideas for how to appropriate the MakeMe cubes. These ideas tended to come towards the end of the lesson once all the activities were completed and the children had more time on their hands. Some were spontaneously suggested while others came about through questioning by the researcher. The ideas for appropriation were not only creative on an individual level but also socially. Children copied and developed another student's idea. This is illustrated by the following example:

In condition 1, towards the end of the lesson, the children begin to investigate new ways of shaking the cubes. First by tapping them with a pencil and then by putting them on the table and then banging the table. The idea passes from student to student until at one point the entire class is banging the table. When asked, several children are able to explain how the cube can sense the movement of the vibrations of the table.

This shows how children engaged creatively with MakeMe and learned more about the sensor through using it in new ways. In condition 2, there was a similar example of an idea being passed around the whole class:

In condition 2, towards the end of the gesturing activity a group of children used the Gesture setting to write their names and then see what colour they came up with. They would then tell their friends "I'm blue" or "I'm red". This idea quickly spreads around the whole class through children watching and copying one another. This happens so quickly it is difficult to find out for certain who first suggested this game but it appeared to be one of the youngest children in the class, a girl aged 6 who is interested to know whether the cube knows her favourite colour from drawing her name.

The writing game may well have been a particularly appealing game for the younger children because it was more imaginative but less challenging than the gestures on the activity sheet. The video analysis also revealed many other ideas that appropriate the way the cube interacts, such as blowing the cube across the table and drawing in the air with eyes closed. As well as directly copying one another's ideas the children also built upon them:

In condition 1, when being questioned about the cube, a girl (M1) says she would put it by her door to tell if anyone came in her room. This is embraced and improved upon by others on her table:

M2: "Or you could put it under your computer in a box or something so that it tells you what times of day [people come in] and so that it takes a picture right in the doorway."

M3: "They would open it and there would be a disco light coming from behind the door, and they would be like 'they're having a disco in there!'"

The conversation then moves to other ideas. Later on when asked to invent additions to the cube M1 suggests:

M1: "I wish it would scan your face and then recognize it."

M3 then links this back to the earlier conversation.

M3: "Then if you had it in your room it would scan your face and say – 'intruder detected!'"

This example, like the other example from condition 1, shows a clear understanding of how the sensor in MakeMe currently works but this case has added ideas for how the cube could be extended to fit their particular idea for an application. There was a similar example of an application idea in condition 2 which showed understanding of how the sensor worked, this time for measuring speed:

In condition 2, during the lesson a boy suggests attaching the cube to his laces to sense how fast he runs so that he can really show who is the fastest. Later, a second boy suggests:

"I'd like more challenges […] You could hold it in your hand and run with it and it could sense your speed or something. Red would equal five miles an hour or something like that."

The first boy then jumps in and says:

"Disco would be like really, really, really fast."

There were also ideas in condition 2 for extending the cube further and making new inventions:

At the end of condition 2 we are chatting about ideas for how they would change the cubes.

R1: "[I'd like them to] move around and connect with each other to build other bigger things."

This idea is not immediately discussed, but shortly after his neighbour suggests a similar idea.

R2: "Why don't you have it so that it can go into different formations? It could go here and here [he moves several cubes together as if building with them] and they would stick together and it would change to dark blue and yellow. And if you put that like that [he piles them up into a tower] they would turn different. They could sync."

R1: "And then all flash together."

R2: "Yeah, turning this bit here into a button. So, if you put it into the formation and then press they would all go together."

This example is particularly interesting because it shows the group that did not experience making the cube, turning the cube itself into a building block to allow them to make things. In general, the ready-made group tended to see the cube more as a building block that could be combined, whereas the making group spoke in more detail about how the panels on the cube worked and how they might change them. This different focus is likely to be due to the way they first experienced the cube, either in pieces ready to be made, or as a ready-made cube.

(iv) Collaboration

The video analysis (Figures 4, 5 and 6) showed clear differences between the two conditions for level of collaboration. Children videoed in condition 1 collaborated much more in both the Making and Gesturing activities than those videoed in condition 2. The type of collaboration was different between the making and gesturing activities. This was characterized in the Making activity by older children checking that the younger children sitting next to them were able to carry out each step in the making process and helping them when needed, as described in the following vignette taken from the video:

An older child and a younger child are putting the first two pieces of the cube together. The younger child sits looking at the wrong piece. The older child looks over to check how she is doing and picks up the correct piece and hands it to her and points to the correct set of pins on that panel. She then continues with her own cube. A few second later she looks across to check the younger child's progress and sees that she is trying to plug the pins into the wrong part of the panel, she points out the correct place. The younger child manages to put the pieces together and then the older child checks the connections are good. From then on, as each instruction is given from the teacher the older child and the younger child build their cubes with their chairs turned to face one another so that the younger child can see how the older child is doing it and the older child can check the younger child is doing it correctly.

This shows a particular property of Making as a challenging activity where the physical nature of the cube enables children to see how others are progressing and offer tangible help. In the Gesturing activity the collaborative behaviour took the form of making gestures together and then seeing what happened. In condition 1, children also collaborated by showing to each other how to get a particular colour and helping their peers to copy them; this did not happen in condition 2. It may be that having the experience of making the cubes together helped them to set up a collaborative relationship that impacted on how they behaved together for the rest of the class.

Condition 2 shows more partial interactions than for condition 1. There were cases where one student might watch another student, without interacting with them, possibly to find out what they are doing. Alternatively, a child might exclaim aloud something about the activity without addressing it to any particular person, e.g. *"I'm blue"* after completing a gesture and getting a colour. In condition 1, these partial interactions would quickly develop into conversations or collaboration, whereas in condition 2 they would stay more distanced. The Gesturing activity encouraged them to watch one another and perform to anyone who might be looking. This appears to come from the public and performative nature of gesturing and the light output it produces. This led to quickly changing conversation groups across the table and around the table. On the other hand, Making encouraged close collaboration in pairs sitting next to one another.

In the Making activity there was more teacher interaction with the researcher giving instructions to the whole class. In the Gesturing activity, interaction with the teacher was informal with the teachers and researcher going around the class doing the activities with different children for short periods. In condition 1, the children sought out their teacher to show her their achievements when they had mastered a difficult gesture or found a new way to make a colour. Towards the end of the lesson four or five children began to teach their teacher how to use the cube in special way. When she finally managed it the children congratulated her: *"You've done it Miss!"* This accounts for the higher levels of teacher interaction in condition 1 compared to condition 2.

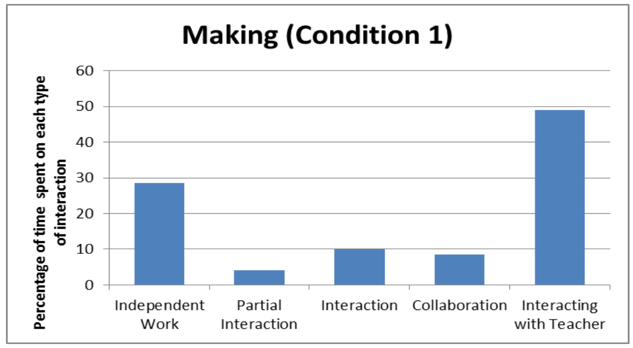

Figure 4: Time spent on different activities while making MakeMe (taken from a 10-minute video of 7 participants working around a single table; from Condition 1).

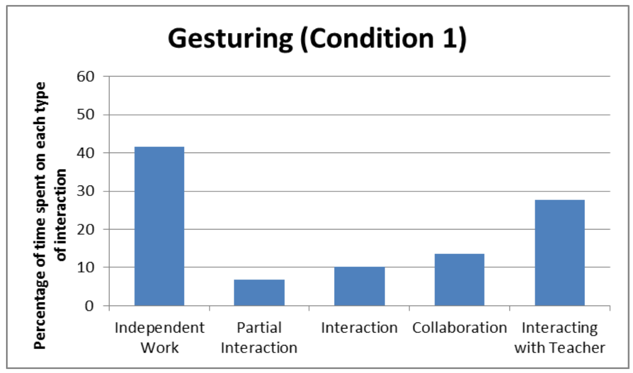

Figure 5: Time spent on different activities while gesturing with MakeMe (taken from a 10-minute video of 7 participants working around a single table, from Condition 1 so participants had previously done the making activity together)

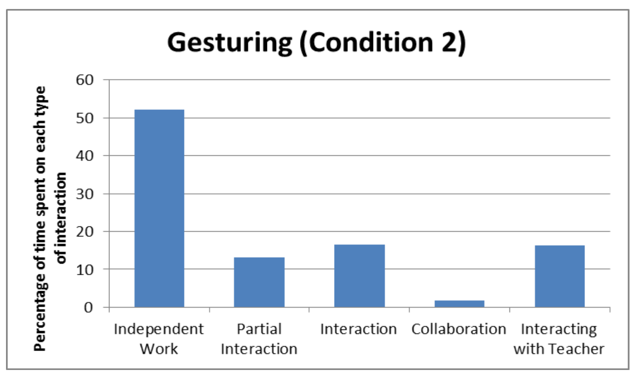

Figure 6: Time spent on different activities while gesturing with MakeMe (taken from a 10-minute video of 6 participants working around a single table; from Condition 2 so participants had not done the making activity together).

DISCUSSION

Our findings have shown how making can play an important role in learning about computing technology, especially in terms of enhancing retention and encouraging collaboration. The results suggest that the learning involved in the constructing of the cube was different to the subsequent shaking and gesturing activities. While both involve active learning through doing, constructing involves putting together individual tangible components, while shaking and gesturing activities involve experimenting to discover the abstract inner workings of MakeMe.

The quantitative test scores show that making the MakeMe cube first significantly enhanced learning for younger children but not for older children. This partially supports the argument that making a device may be good preparation for learning about how it works. It is likely that the older children did not show improvement due to a ceiling effect. The older children performed so well in the activities and on the test in both conditions that it would be difficult for them to be improved by one condition over another. One argument could be that the older children already had more experience learning about computing technology and were already equipped with the concepts and schemas needed to learn about the MakeMe cube. Whereas, the younger children do not have this prior experience and needed the making activity to prepare them for learning how the MakeMe works. It could be that other kinds of making that are more complex and that aim to communicate more challenging computing concepts would tax older children and lead to a similar effect. Future research needs to explore the effect of using different levels and kinds of making on age-related learning.

Important to the interpretation of the findings was the way that the lesson set-up influenced the results: in particular, the mixture of ages in the classroom. Interestingly there were higher levels of collaboration observed in the making condition. This suggests another explanation for the difference between the older and younger students. Vygotsky's Zone of Proximal Development (ZPD) [41,42] is a concept that describes what a learner is able to do under guidance compared to what he or she would be able to do unaided. It may be that the learning objectives in the MakeMe lesson were within the older children's unaided ability. Whereas, for the younger children, the learning objectives may have been in their Zone of Proximal Development: only accessible to them with guidance. In condition 1, the older children helped the younger children much more and may have provided the guidance needed. In condition 2, the children collaborated less and the younger children did not have access to the same level of peer support.

This highlights a positive attribute of including making in the classroom: it appears to promote collaboration between peers. Making and Gesturing were found to support different kinds of social learning: making seems to encourage close collaborative help between children, and the gesturing activities take the form of watching and performing for one another. In their review of computational participation inside and outside of schools, Kafai and Burke [22] challenge teachers to find a way to bring the participatory approach found in online communities into the classroom. Our study shows that physical construction could be one way to promote this desired collaboration in the classroom. Our findings come from a mixed age and ability class where the seating plan and the level of challenge encouraged young and old children to collaborate. Further research is needed to examine the interplay between making, collaboration and learning for different types of classes and mixes of age and ability.

More generally the tactile, physical and visual attributes of the MakeMe kit seemed to encourage using the cubes as "objects-to-share-with". All the activities in both conditions inspired creativity and appropriation of the cubes for new uses. However, our results indicate that what they suggested tended to be different depending on how they had experienced the cubes. Experiencing something as a set of pieces to put together seems to stimulate ideas at the level of changing the component parts to make something new. Experiencing something as a finished device stimulates ideas at the level of combining devices together to build something new. From the point of view of PFL, this suggests that the different experiences in the two conditions promoted different schemas for thinking about the MakeMe cubes. This supports the idea that making a device does indeed change the way we think about it.

CONCLUSIONS

The findings from our study suggest several implications for educators and designers of educational kits:

- Making is a valuable part of learning, particularly for younger children.
- Making encourages collaboration. It is well suited to mixed ability classes
- The way computing technology is presented to children impacts the creative ideas they have.
- Making encourages ideas on the level of individual component parts. Interaction with ready-made devices encourages higher-level ideas, which use the device as a building block.

In sum, our in-situ experiment demonstrates that the process of making can improve the learning of computing technology while making it engaging and collaborative. The use of ready-made electronic kits, however, can focus the child's mind at a different level of granularity, when using them that can lead to different ideas being explored. Hence, it is not a question of either adding making or not to lessons on computing technology, but when best and how. Curriculum development for computing technology needs to consider how best to design lesson plans, in terms of when to begin with making tasks and when to start a lesson using ready-made kits. Both provide different ways of setting the stage for subsequent learning activities but making seems to provide a starting point for deeper understanding, sharing, reflecting and creativity.

PARTICIPATION AND SELECTION OF CHILDREN

In this study 96 children aged 6-11, from two state primary schools in a rural area of the UK were recruited. Prior to the study UCL ethical approval was obtained. Selection was by virtue of them being in the school classes that were invited by their teachers to do the work. Prior to the study information sheets were sent to parents and parents signed and returned consent form for their child to take part. The children were told about the aims of the research and what data was being collected about them at the start of the lesson. The children were then asked if they would like to take part and gave their consent verbally.

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