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Esme Bridget Glauert [a]
[a] Institute of Education , ECPE , London, UK

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RESEARCH REPORT

How Young Children Understand Electric Circuits: Prediction, explanation and exploration

Esme Bridget Glauert*
Institute of Education, ECPE, London, UK

This paper reports findings from a study of young children's views about electric circuits. Twenty-eight children aged 5 and 6 years were interviewed. They were shown examples of circuits and asked to predict whether they would work and explain why. They were then invited to try out some of the circuit examples or make circuits of their own choosing. Children expressed a variety of views about the connections needed in a circuit, offered different kinds of explanation and showed differing levels of competence in circuit making. The range of responses showed similarities to those of older students found in previous research. The relationship between practical competence, prediction, and explanation was not straightforward. For example, children with similar levels of practical competence made different predictions or offered different kinds of explanation. Analysis of the circuits children chose to construct suggested influences of existing competence and knowledge. In particular, some children tested out circuit examples about which they had been unsure during the interview, while others explored circuit connections more generally. Findings underline the importance of drawing on a variety of evidence in assessing young children's understandings of electric circuits. They indicate that young children may offer views about electric circuits not unlike those of older children and adults with similar experience. Finally, there was some suggestion that the interview procedure may have acted as an instructive stimulus in helping children to become more conscious of their own views and reflect on their thinking in the light of further evidence.

Introduction

Background

This paper presents findings from a study of 5-year-old and 6-year-old children's views about electric circuits. The study formed part of a wider investigation into young children's responses to classroom activities in electricity (Glauert, 2005),

*Institute of Education, ECPE, 20 Bedford Way, London WC1H 0AL, United Kingdom. Email: e.glauert@ioe.ac.uk

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which sought to explore both the nature of children's explorations and evidence of their thinking in relation to simple electric circuits. The present study set out to investigate young children's views of the connections needed in a circuit (*how* to make circuits) and to probe their explanations for their views (*why* circuits need to be connected in particular ways). It sought to explore relationships between children's views of connections needed in a circuit, their explanations, and the kinds of practical explorations they undertook with simple circuit components.

The study was prompted by interacting professional and research interests in early years science and assessment practices in primary schools. In recent years there has been growing attention to children's learning in the early years of schooling in the UK. The recognition of the importance of this phase of education is reflected in the introduction of the Curriculum Guidance for the Foundation Stage (Qualifications and Curriculum Authority [QCA], 2000) and the large-scale research undertaken by the Effective Provision of Pre-School Education Project (e.g., Sylva et al., 1999; Sylva, Melhuish, Sammons, Siraj-Blatchford, & Taggart, 2004). In addition, science has become more fully established as part of the early years curriculum since the introduction of the National Curriculum in 1989 and the inclusion of science in the Curriculum Guidance for the Foundation Stage (QCA, 2000) as part of the area of learning entitled Knowledge and Understanding of the World. Research is providing increasing evidence of young children's capabilities in science (British Educational Research Association, 2003; Brown, Campione, Metz, & Ash, 1997; Siraj-Blatchford & Siraj-Blatchford, 2002). The papers presented on 'emergent science' at recent conferences held by Bishop Grosseteste University College in 2006 and the Association for Science Education in 2007 indicate growing research interest in this area. However, much is still to be learnt about how thinking in particular domains develops and how best to support young children's progress. It is therefore timely to evaluate what young children might be gaining from the common science activities to which they are now being exposed. In particular, given the emphasis on practical activity and children's enquiries in current guidance and policy on learning and teaching in science (Department for Education and Employment, 1999; QCA, 2000), an examination of the kinds of interaction there might be between children's practical experience and their thinking about phenomena is of particular relevance to practitioners in the early years.

The present study was also informed by the increased emphasis on the role of formative assessment in supporting learning and teaching in schools (Black, Harrison, Lee, Marshall, & Wiliam, 2003; Clarke, 2001; Stobart & Gipps, 1997). This poses challenges for practitioners both in clarifying what they are looking for and in developing approaches to assessment that will provide insights into learning processes and useful information to inform teaching. The study of primary science carried out for the Wellcome Trust (Murphy & Beggs, 2005) and the Office for Standards in Education report on science in primary schools (Office for Standards in Education, 2005) suggest that formative assessment practices are still relatively underdeveloped in schools. In the early years there are particular considerations in developing and employing approaches to assessment sensitive to young children's thinking. Research in developmental psychology has drawn attention to the different responses children may make in different situations and the possible dangers inherent in adopting a single one-off approach to eliciting children's ideas. For example, responses may depend on the context or whether they are child or adult initiated. (See, e.g., Carey, 1985; Donaldson, 1986.) There may be a mismatch between children's views expressed through their talk and actions (Karmiloff-Smith, 1992; Piaget, 1977, 1978). Or as Brown et al. (1997) suggest, there may be a difference between what children choose to say or do and their capabilities. For example, although research indicates young children are capable of developing knowledge through their practical enquiries (Metz, 1998) or of offering explanations (Karmiloff-Smith & Inhelder, 1974; Metz, 1991), this may not be revealed without prompting. It is therefore important to collect a variety of evidence of their views and capabilities and to seek to elicit children's reasoning behind their views to aid interpretation of their comments and actions. The present study set out to develop productive approaches to investigating young children's thinking in electricity.

Previous Work in Electricity

Electricity was selected as a context for the research as it is a topic commonly addressed in early years settings. It offers opportunities for practical investigations and for children to demonstrate knowledge and understanding both through talk and activity. Students' understandings of electric circuits have been studied extensively over the past 20 years, covering a wide range of age groups from primary to university level. However, limited research has been carried out with the youngest children in primary school. A variety of methods has been employed from observations of practical activities to interviews and paper-and-pencil tests. The specific aspects of electricity addressed and methods selected have varied taking into account the age and experience of subjects. Studies have explored, for example:

- pupils' views about the properties and uses of electricity (Osborne, Black, Smith, & Meadows, 1991; Solomonidou & Kakana, 2000);
- connections in circuits (Asoko, 1996; Osborne, 1983; Osborne et al., 1991);
- models of flow of charge in an electric circuit (Asoko, 1996; Osborne, 1983; Shipstone, 1984); and
- forms of explanation (Asoko, 1996; Shepardson & Moje, 1994).

The present study built on these findings and sought to extend knowledge in a number of ways. It set out to examine in detail what young children were gaining from their school experiences of circuit-making by investigating not just their views about circuit connections but the kinds of explanations they offered for what is happening in a circuit. The nature of the interactions between children's explorations, predictions and explanations in electricity was of particular interest. The study sought to investigate how far the views of young children corresponded to those of older children and adults found in previous research. Finally, it was hoped that the study might offer frameworks and approaches that could be employed in assessing young children's learning in electricity.

Method

Approach to Data Collection

An interview framework was devised to investigate children's views about electric circuits based on that employed in an earlier study (Glauert, 2005). The approach to data collection was designed to provide children with a range of different opportunities to show what they knew and could do. The interview was divided into two parts. The first part of the interview was designed to probe children's views of the connections needed in a circuit and their explanations for their views. The second part provided an opportunity to study the nature of children's practical explorations of electric circuits. This made it possible to examine relationships between children's predictions and explanations offered in Part 1 and their explorations undertaken in Part 2. Interviews were audio-recorded and fieldnotes made during both parts of each interview. Care was taken to include details of children's actions that might be helpful in interpreting children's responses. Further information is provided below.

In the first part of the interview children were shown examples of circuits, asked to predict if they would work, and to explain why. Children's predictions, explanations, and actions were recorded on a prepared chart. The order of presentation of circuit examples was noted. This enabled details of children's talk to be checked on the audiotape of the interview if needed. It was anticipated this might prove useful in the subsequent analysis, particularly in the examination of children's explanations. The choice of circuit examples for the interviews was informed by Osborne et al.'s (1991) study of children's views of electric circuits, which included children aged 5–7 years. Their findings suggested critical differences between children's models of what makes circuits work dependent on their understanding of the number and nature of the connections between the source of electricity, such as a battery, and the device. Based on their work, six progressively more sophisticated models were distinguished as follows:

- Model A: everything works.
- Model B: a single connection only on the battery/device.
- Model C: two connections (incorrect) – one connection only on the battery/device.
- Model D: two connections (incorrect) – two battery connections, two device connections (incorrect).
- Model E: two connections to both battery and device using two wires.
- Model F: two connections to both battery and device (two wires not needed).

Model A assumes that a device will work even if there are no connections between the battery and the device. Models B–D recognise the need for the battery to be connected to the device but do not accurately represent the nature of the connections: Model B assumes only one connection is necessary, Model D assumes two connections are required, both to the battery and the device, but does not distinguish between the different poles of the battery or connecting points on the device. Model C assumes two connections are required on the battery and the device; the need for a connection from each pole of the battery to the device is recognised but the two connecting points on the device are not correctly identified. Model E accurately represents how the device and battery should be connected but assumes two wires are required. Model F also accurately represents how battery and device should be connected but acknowledges that the connections required can be achieved with one wire.

Differentiation between these models was accomplished using the rule assessment technique developed by Siegler (1976). Children were presented with a set of circuit examples designed to discriminate between models and asked to predict which would work. This made it possible to determine which characteristics of circuits were salient to them. Table 1 presents the set of circuit examples developed for the present study. Each circuit example was shown to each child on three separate occasions. Children's predictions were then compared with the patterns of performance attributable to each model indicated in Table 2.

Responses to Circuit 8 are uncertain for Models C and D as these models focus on children's awareness of the connections needed and not the number of wires required. Circuits 4, 5, and 6—designed to explore children's models of the specific connections needed—are all constructed with two wires. (It would be possible to hold a two-connection (incorrect) model and predict that Circuit 8 with one wire would work.) It is important to note that although the models increase in sophistication, this does not simply translate into increased overall performance: some circuits, notably a complete circuit made by directly connecting one terminal of the device to one pole of the battery and using a single wire to connect the other pole to the other terminal, may be judged correctly by children with simple conceptions of circuits (Models A and B), and may be misjudged by children with more sophisticated models (Models C–E).

It was considered that children's explanations for their predictions might provide additional evidence of their views of the connections needed in a circuit, and in some cases their models of flow of charge. A precise correspondence was unlikely for two

Table 1. Circuit examples

Example	Circuit characteristics
1	One wire only—incomplete circuit
2	Two wires—gap in the circuit
3	No wires
4	Two wires—complete circuit but one connection only on the battery
5	Two wires—complete circuit but one connection only on the device
6	Two wires—complete circuit, two connections on the device but incorrect
7	Two wires—complete circuit, correct connections
8	One wire only—complete circuit, correct connections

Table 2. Number of correct responses predicted by consistent use of each model of the connections needed in a circuit

Model	Predicted response to each circuit example								Total correct
	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Circuit 6	Circuit 7	Circuit 8	
A	0	0	0	0	0	0	3	3	6
B	0	0	3*	0	0	0	3	3	9
C	3*	3*	3	0	0	0	3	0–3	12–15
D	3	3	3	3*	3*	0	3	0–3	18–21
E	3	3	3	3	3	3*	3	0	21
F	3	3	3	3	3	3	3	3*	24

Notes: Each circuit was presented three times. 1 = correct response, 0 = incorrect response.
*Circuits designed to distinguish between successive models.

reasons. First, Shepardson and Moje (1994), who studied much older children in the fourth grade, suggest there are complex interactions between pupils' knowledge of the connections needed in a circuit, their models of flow of charge, and the nature of the explanations offered. Also, work in developmental psychology suggests that during development children can show discrepancies between their procedural competence and their conceptual understanding (Rittle-Johnson & Siegler, 1998). The discrepancy is not always in the same direction. In the case of arithmetic, some children show understanding of arithmetical principles that is considerably in advance of their skill in calculation whereas others show considerable proficiency in calculation but limited conceptual understanding (Dowker, 2005).

In the second part of the interview, children were provided with a range of components (batteries, bulbs, motors and wires) and invited to make circuits of their own choosing. In particular it was suggested that they could try out any of the circuit examples shown in Part 1 of the interview. The intention was to compare children's practical competence and reasoning shown in action through their explorations with more explicit views revealed through their predictions and explanations. Children were left to undertake their own explorations. However, on a few occasions, after repeated attempts to get devices to work, children asked for help. In these instances the researcher pointed out connections needed. Apart from this the only involvement of the researcher was to ask children whether they wished to try out anything else. Careful fieldnotes were made of the sequence of each child's explorations to accompany the audiotape record. These included details of any circuit cards selected, drawings of circuits constructed, children's comments, and any assistance given.

Participants

A Year 1 class of 28 children, consisting of 12 girls and 16 boys, aged 5 and 6 years, participated. The class was in an inner-city school, which takes children from a wide range of ethnic, linguistic, and socio-economic backgrounds. The children had studied electricity in the previous year. The teacher had provided opportunities to explore making circuits with bulbs, motors, and buzzers. They had received no further teaching in electricity.

Procedure

Children were interviewed individually. In the first part of the interview they were shown examples of eight circuits made with a flat battery, with characteristics as in Table 1, and asked to predict whether they would work if the battery was replaced with a new one. The circuits were shown in photographs and also presented using practical equipment. Children were encouraged to offer reasons for their predictions. In the case of the circuits they thought would not work, they were invited to suggest what would be needed to make the circuit work. To assess consistency of response, children were presented with each circuit three times. Three sets of photographs were prepared of the eight circuits selected. Each set was mounted on card of a different colour. Each set was taken in turn and the photographs presented in random order. In the second part of the interview, children were invited to make circuits and encouraged explicitly to try out any of the previously shown circuits that interested them. Interviews were audio-recorded. Children's responses to each circuit example were recorded on a chart and field notes were made of children's actions and comments during both parts of the interview.

Approach to Analysis

Children's predictions. The number of correct predictions made by each child for each circuit was recorded and the results for the class ordered according to the number of correct predictions made. The number of circuits for which each child changed his/her predictions across the interview was noted. The pattern of prediction for each circuit was examined to determine whether changes in response represented improvement or decline in performance across the interview. Children's explanations were used to explore possible reasons for any changes in children's views.

To examine models of the connections needed in a circuit that might underlie children's responses, their predictions were then compared with patterns of response associated with the different models of the circuit as shown in Table 2. Both the overall number of predictions that matched each model and the more detailed pattern of predictions across the circuit examples were used in identifying the model(s) that most closely corresponded with each child's responses. A chart was constructed showing for each child how many of his/her predictions were consistent with each model. A score of 24 indicated a complete match. A score of 21 or more was taken to indicate a reasonably good match as the number of correct responses increases by at least three for each successive model (see Table 2). Where a match of less than 21 was recorded, a more detailed examination of children's predictions was used to identify possible models corresponding to children's responses.

Children's explanations. The analysis of children's explanations offered a further opportunity to consider the nature of their reasoning about electric circuits. It was possible to examine how far children's explanations were consistent with the models of the circuit suggested by their predictions and to gain additional insights into the thinking underlying their judgements. The categories used to analyse children's explanations were based on those developed in an earlier study (Glauert, 2005) and are shown in Table 3 with examples of explanations given in each category.

Table 3. Categories of explanation

Category	Examples of explanations in each category
Components	Needs new bulb/battery
	Needs wire(s)/got wires
Connections	Gap/not attached/not touching/joined
	Wrong/missing connections
	Correct connections
	Joined circle
Power from the battery	No power
	Not so much power
	Is giving power
Path for electricity	No path for electricity
	Power/electricity cannot go that way
	Metal not touching/plastic/glass blocks
	Electricity goes all round the wires

Children's explorations. Children's explorations in the second part of the interview were studied to gain further information about their practical competence, response to the interview procedure, and views about electric circuits. Field notes and audio recordings were analysed to examine the nature of children's explorations. An initial review of children's responses showed four common areas of activity:

- Trying out circuit examples using the cards prepared for the interview.
- Exploring circuits to make the bulb light.
- Making the motor work.
- Exploring batteries in a circuit (e.g., changing battery connections or the number or types of battery).

General features of children's response were reviewed in relation to the four activities commonly undertaken.

Relationship between children's predictions, explanations, and explorations. Finally, children's responses to the two parts of the interview were reviewed to explore relationships between children's predictions, explanations, and explorations. A chart was constructed to summarise children's responses to the different parts of the interview.

From the first part of the interview the chart showed children's models of the connections needed in a circuit and the nature of their explanations. From the second part of the interview the chart indicated which of the four common activities children had undertaken and whether they were successful in making the bulb and motor work. This made it possible to examine patterns in responses across the class; for example, whether children with different models of the connections needed in a circuit undertook different forms of exploration, or how far children's circuit knowledge in action was reflected in their predictions and explanations.

Results

Results for the two parts of the interview are presented in turn. First, children's predictions are reported. Any variation in children's predictions across the interview and models of the circuit that might underlie their predictions are considered. The kinds of explanations offered by children for their views are examined. Then the nature of children's explorations in the second part of the interview is reviewed. Finally, relationships between predictions, explanations, and explorations are identified. In the presentation of results, pseudonyms are used to protect anonymity.

Children's Predictions

One child predicted all of the circuits would work, giving a score of 6 out of a total of 24 possible correct responses. Nine children made between 8 and 10 correct predictions. They recognised the need for some connection between the battery and the bulb. However, their responses gave no indication of an awareness of the need for a complete circuit and for two connections on the battery and bulb. The remaining 18 children with scores of over 11 made predictions that suggested a growing recognition of the need for two connections between the battery and bulb. The two specific connections required on each device were only substantially recognised by seven of these children. Predictions for Circuit 8 (the complete circuit made with one wire) were variable and did not necessarily improve with a growing recognition of the specific connections needed in a circuit.

Variation in predictions. There was some variation in the predictions individual children made for each circuit. Across the interviews as a whole there were 48/224 occasions when children changed their predictions in relation to a particular circuit. The majority of changes (33/48) were in the direction of improvement. This trend was reflected in relation to all circuits except the complete circuits made with one or two wires. A more detailed examination was undertaken of the responses of the four children (Anna, Maruf, Benedicta, and Anil) who showed the most variation in response to see whether this suggested what might have contributed to these changes in view. They had all changed their views in relation to four circuit examples. With the exception of Circuit 8 (the complete circuit made with one wire), three of the children made changes in predictions from an incorrect to a correct response. Comments suggested an increasing awareness of the two connections needed on the battery/device for example:

> No that needs one (connection/wire) … and … need to move one wire. (Anna)

> Need another to stick. (Maruf)

> They aren't stuck together in the right place. (Benedicta)

The changes in the predictions of the fourth child, Anil, were mostly in the opposite direction, from a correct to an incorrect response. In explaining his first two predictions for Circuit 1 (one wire—incomplete) he said explicitly that another wire was needed to join the battery and bulb holder. At the final presentation of this circuit he said it would work. The reason for this was not clear, as he offered no explanation. In response to the final examples of Circuit 4 (two wires—one connection only on the battery) and Circuit 7 (two wires—correct connections), he explained his change in predictions by suggesting that a wire had to be connected to the bump on the positive terminal of the battery. This may have been a consequence of the way the circuits were presented. In some examples a crocodile clip was attached to this part of the battery, and in his increasing attention to the details of connections he may have concluded this was essential. In relation to Circuit 8 (the complete circuit with one wire), three of the children (Anna, Benedicta, and Anil) initially said it would work but then decided two wires would be needed. The remaining child (Maruf) initially suggested another wire was needed. When shown the final example he said it would work but did not give any reason for this change in view.

In reviewing children's predictions alongside their explanations across the class as a whole, a similar picture was obtained. In general the explanations offered for predictions did not suggest an arbitrary approach to response. They indicated some improvements in response as specific connections required were recognised. However, they also revealed less productive changes in thinking, for example, that two wires are always required or that wires need to be connected to particular points on the battery terminal.

Models of the connections needed in a circuit. The predictions made by 23 children showed a reasonable match with one of the proposed models, as indicated in Table 4.

Further detailed analysis of the pattern of predictions of the remaining five children indicated that two children's responses showed characteristics of both Models B and C, in indicating some recognition of the need for two connections. Two children gave responses corresponding to a mixture of Models C and above in articulating the need for two connections and beginning to identify the correct connections needed. The final child's predictions corresponded most closely to Model E.

Overall, the pattern of responses across the class suggested a range of views. One child did not indicate the need for connections between the battery and bulb (Model A). About one-third of the children (nine children) held a one-connection view (Model B). The remaining two-thirds (18 children) showed some recognition of the

Table 4. Number of children whose predictions matched each proposed model of the connections needed in a circuit (n = 28)

Model	Model description	Number of children
A	Everything works	1
B	1 connection	9
C	2 connections (incorrect), 1 connection to battery/device	7
D	2 connections (incorrect), wrong connections	1
E	2 connections (correct), two wires needed	4
F	2 connections (correct)	1
No clear match to any model		5

need for two connections (Model C and earlier transcript). However, only five children indicated an awareness of the two correct connections required on the battery and device (Model E), and only one child recognised that these two connections could be achieved with one wire (Model F).

Children's Explanations

The children gave a range of kinds of explanation for their predictions. Many commented on *how* to make a circuit, and the components and connections needed. A few indicated they were beginning to think about *why* circuits were connected in particular ways in discussing a path for electricity. One child referred to the power of the battery. Some children gave a limited number of explanations. They were mostly in the Model B group. The Appendix provides full details of the categories of explanations given by each child. It also shows their relationships with children's practical competence and the models of the circuit that best matched children's predictions.

The explanations of the Model B group (one connection) focused predominantly on the components needed in a circuit. Children with the more developed models of the circuit offered explanations that reflected an explicit awareness of the connections needed; for example:

> No, that's not connected to the battery. (Basil, Model D) or
>
> No that one has got to be there and that one has got to be there [pointing to the correct connections on the battery and bulb]. (Cairo, Model C) or
>
> No, the light bulb needs one there. (Anna, Model C).

Furthermore the explanations given by some the children whose predictions corresponded to more than one model of the circuit reflected the different levels of circuit knowledge shown in their responses to the circuit examples. For example, Joseph's (Model B/C) explanations referred not just to components (common for Model B) but also to the connections needed, a form of explanation often associated with Model C. A developing awareness of connections was expressed for example in commenting they had 'got to be properly'. However, the lack of reference to the specific connections is in contrast to the more explicit indications of the connections needed offered by children with more developed models of the circuit (as shown in the examples on the previous page).

While children's explanations generally provided evidence of their developing thinking about electric circuits in line with their predictions, the relationship between predictions and explanations was not always straightforward. For example, while only a few children gave explanations that began to consider the path for electricity round a circuit, these responses were not confined to the groups of children with the most developed views of the connections needed. Two children in the Model B group gave responses with words and gestures that suggested reference to the path for electricity.

> You have to make a circle—electricity goes [moving his hand round and round a complete circuit]. (Kendell, Model B)

> Electricity goes through here and then through there and then makes the light work [pointing round the circuit, from one battery terminal to the other]. (Javid, Model B).

Finally, the analysis of children's explanations for their predictions in relation to the complete circuit made with one wire gave some further support for the suggestion from children's predictions that, in focusing on the correct connections needed, children might develop an idea that two wires would be required to make a circuit work. One-half of the children whose predictions corresponded to Models C or D gave some responses that indicated they thought the complete circuit with one wire would work, mostly focusing explicitly on the connection between the clip attached to the bulb holder and one of the battery terminals to justify their view. The remaining children holding Models C and D and all the children who gave predictions that matched Model E not only predicted that Circuit 8 would not work but commented explicitly on the need for two wires for example

> No, need another wire. (Benedicta, Model E)

They gave no explanations that focused on the complete circuit. Responses suggested that in grappling successfully with the exact details of connections, as reflected in their explanations, some children lost sight of the over-riding idea of a complete circuit. The one child whose predictions matched Model F referred explicitly in her explanations to the fact that the complete circuit with one wire was all 'joined up'.

Children's Explorations in the Final Part of the Interview

After a fairly demanding interview, all children were still keen to participate in follow up activities.

Trying circuit examples. Most children (19/28) tried circuit examples. The actions and comments of some suggested a deliberate choice in selecting circuit examples about which they had been unsure or had changed their view during the course of the interview. The vast majority of circuits (95/98) were made accurately to match those shown on the cards, even by children in the Models A and B groups. This indicated attention to the detail of connections and a level of practical competence not always reflected in children's predictions or explanations earlier in the interview. Over one-half of the children (10 children) who tried circuit examples were able to correct them easily. These often included examples for which they had made incorrect predictions in the structured part of the interview. In some instances, children's talk during their circuit making offered further insights into what they were gaining from this experience. For example in correcting Circuit 4, Javid (Model B) said 'one has to be there … won't work if not stuck on like that' and Sarfaraz (Model C) commented 'It does not work. One has to be there. Now I know what to do'. Several children commented that the complete circuit with one wire did work for example 'It did work—on and off—connecting and disconnecting the wire on the bulb holder (Nesha, Model B). 'It works because that [the clip] is touching that one [the battery terminal]. It does work' (Mariama, Model E). It is possible that the interview procedure helped to focus attention on the detail of particular circuits and in some cases raised specific questions the children wished to pursue. This was also implied by the deliberate choice of circuit cards made by some children.

Making the bulb light. All of the children tried to make the bulb light during this part of the interview. Most children (22/28) were able to light the bulb quickly and easily. A further two managed to light the bulb after further explorations. Only four were unable to light the bulb without help, all four in the group who made predictions consistent with Model B (one connection). The success of the majority of the children in lighting the bulb indicated that many children were competent in circuit-making even if they did not identify or articulate the correct connections needed in discussing the circuit examples.

Wider explorations. Six children undertook wider explorations. Five tried making simple circuits using different numbers or colours of wires or making connections to different parts of the battery or bulb. All of these children had either taken time to light the bulb or had needed help to be successful, suggesting these explorations were characteristic of children who were still exploring circuit connections. In contrast the sixth child (Eduardo, Model C), who was very confident in circuit-making, did not focus on the connections needed but tried to find a way to get the bulb and the motor to work simultaneously. Examples are shown in Figure 1.

Making the motor work. Most children (24/28) tried to make the motor work. The majority (17/24) were able to do this quickly and a further five succeeded without

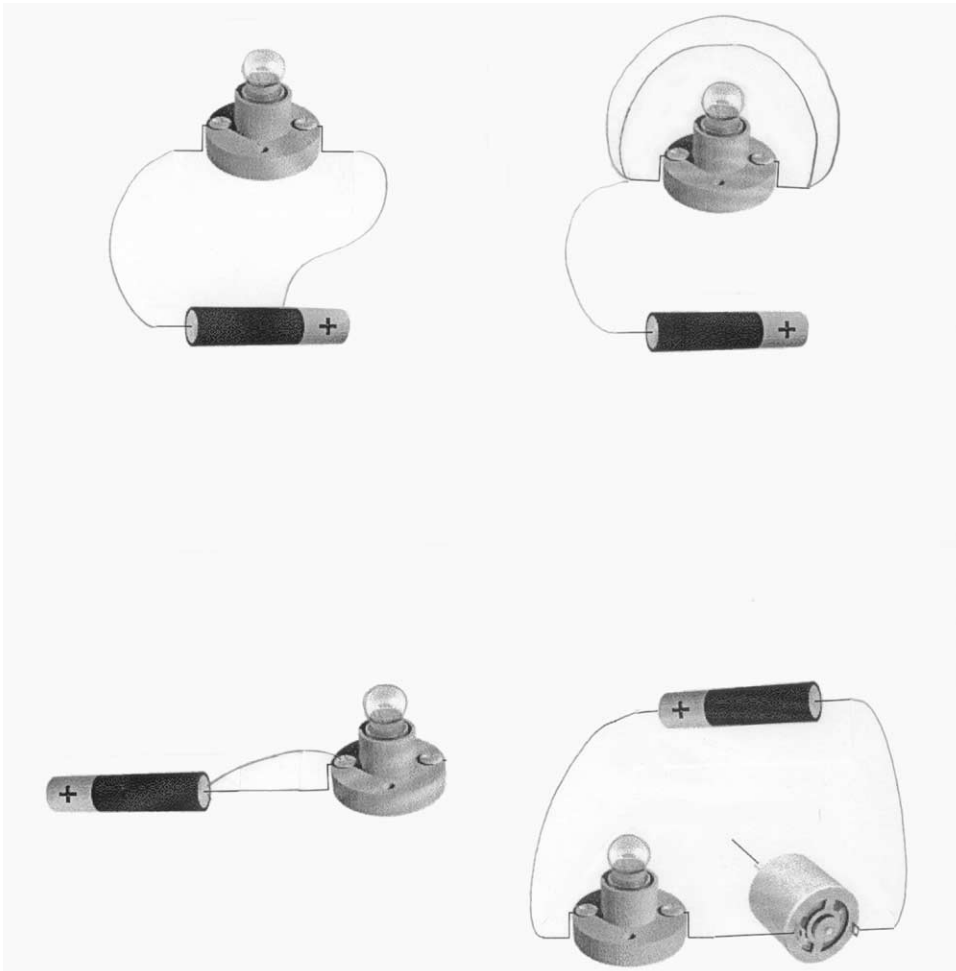

Figure 1. Examples of children's wider explorations: top left, Alexandre (Model B); top right, Sabrina (Model B); bottom left, Kingsley (Model B); bottom right, Eduardo (Model C)

help once they had located the correct connecting points. Only two needed support to make the motor work. In reviewing children's circuit-making with the bulb and motor there was no strong indication that one device caused more difficulty than another. In a few cases, children just needed time or help to find the connecting points on the motor.

Exploring batteries. Just over one-half of the class (15 children) experimented with batteries. Two children set out to try different sizes of battery and two tried turning batteries round in their circuit. Twelve children explored adding more batteries in a circuit. Of these, most (10 children) commented explicitly on the effects of further batteries in a circuit for example:

> If you have three batteries it [the motor] will go fast. (Sarfaraz)
>
> [Raisha predicted the motor would] go faster with two batteries [and suggested] the paper [on the spindle] might fly away if I had four. (Raisha)
>
> [Anna tried the light bulb with increasing numbers of batteries] the light gets very strong. (Anna)

They were able to link cause and effect in commenting on the relationship between the number of batteries and the performance of a device.

Relationship between Predictions, Explanations, and Explorations

The explorations undertaken by children in the final part of the interview gave further insights into children's practical competence in making circuits. This made it possible to compare children's practical competence, their views of the connections needed in a circuit, and the kinds of explanations they offered. Looking across the groups of children who held different models of the circuit, some overall differences could be observed in their practical explorations. The 16 children whose responses to the circuit examples indicated they were becoming consciously aware of the specific connections needed (Model C onwards) were all very successful in making both the bulb and motor work. A high proportion of these children (13/16) undertook focused trials of particular circuit examples. Many (10/18) explored adding several batteries to a circuit, often commenting on the effects on devices. The wider explorations undertaken by one of these children (Eduardo) focused not on making a simple circuit, but on ways of connecting several batteries or devices in a circuit.

In contrast, the explorations of the 12 children whose predictions corresponded to Models A and B (no connection and one connection) suggested that some were still at an early stage of gaining practical competence in circuit-making. Six of them had difficulties in making devices work. Five of these six tried out different connecting points on the battery and bulb or investigated changing the number and colours of wires in a circuit. No other children undertook wider explorations of this kind. In comparison with children holding two-connection models of the circuit, a smaller proportion of the children whose predictions corresponded to Models A and B tried circuit examples (6/12) or experimented with batteries (5/12) and they made fewer comments on the results

However, a more detailed examination of the results indicated that practical competence was not always associated in a simple way with models of the circuit or forms of explanation. Most children in the class (22/28) could make circuits independently, showing *in action* a two-connection (correct) model of the circuit. However, only six children could recognise and make explicit all the detailed connections required through their predictions and explanations. Thus, in many cases (16/28), children's models of the circuit shown in action were in advance of those suggested by their predictions. For the remaining 12 children, their models of the circuit indicated in their circuit-making matched those suggested by their predictions. That is, all six children who had difficulties making devices work held a one-connection model of the circuit and the six children with a two-connection correct model could make circuits successfully.

As discussed earlier in the paper, the relationship between children's predictions and explanations was also not straightforward. All children offered explanations referring to *components*. Explanations related to *connections* were more common in children whose predictions were characteristic of two-connection models of the circuit (Models C–F). However, one-half of the children with a one-connection model also gave explanations referring to *connections*, including three children (Alexandre, Kingsley, and Sabrina) who were not yet competent in circuit-making. In particular, Javid focused on connections in explaining his views in relation to 11/24 of the circuit examples. Finally, explanations referring to the *power of the battery* or *path for electricity* were not only offered by children holding the most advanced models of the circuit. Of the six children who gave these kinds of explanations, two held a one-connection model of the circuit, one of whom (Kingsley) had difficulty in making devices work in the final part of the interview. (Full details of children's practical competence, models of the circuit, and the kinds of explanations they offered are provided in the Appendix.)

Discussion and Conclusions

The interview procedure provided a variety of evidence of young children's thinking about electric circuits. It enabled an examination of children's models of the circuit and the nature of their explanations for why circuits would or would not work. Although limited in scope, children's explorations in the final part of the interview gave some further indication of their developing thinking about electricity as well as their competence in making circuits. This made it possible to explore relationships between children's practical competence, predictions, and explanations and to consider the reasoning that might underlie children's responses.

Predictions

As in previous studies involving older primary and secondary age students, children made predictions in relation to the circuit examples characteristic of a range of models of the circuit. Almost all children appreciated the need for connections from the battery to the device. A number articulated a need for a complete circuit, but only a small proportion identified all the specific connections needed. The present study suggests that, in the process of developing a more explicit awareness of the connections needed, children may develop a view that complete circuits can only be made with two wires, particularly if they have had little practical experience of circuit arrangements with one wire. The range and distribution of responses was similar to that reported by Osborne et al. (1991) for the infant children in their sample. Findings also showed parallels with Asoko's (1996) study of older primary children aged 8 and 9 years, in that while most children were able to identify the need for two connections on the battery or device, many did not notice incorrect connections and some thought that two wires would be necessary to light the bulb.

Questions of consistency. Questions about the coherence of young children's thinking and the consistency of the views they express in different contexts emerge frequently in discussions of conceptual change and of children's enquiry processes (Kuhn, 1989; Osborne, 1983; Osborne et al., 1991). In the present study some inconsistency was found in children's predictions for the circuit examples. The analysis of patterns in children's predictions and the nature of their explanations made it possible to study this inconsistency in some detail. As illustrated in the examples discussed earlier, in most cases children's explanations gave some indication of the thinking behind their changes in view. Overall, the analysis of children's explanations gave no suggestion that children were responding in an arbitrary way to circuit examples. Children's comments suggested that variations in predictions were the product of changes in thinking. Siegler (2000) suggests that what he terms variability (rather than inconsistency) is often predictive of change, indicating cognitive conflict or openness to new ideas. Indeed there were indications from children's follow-up explorations that variation might offer productive starting points for learning and teaching. Findings from this study suggest this might be a fruitful area for further investigation.

Explanations

The study set out deliberately not just to probe children's views of the connections needed in a circuit but to examine the nature of the explanations they offered for their views. Children offered a range of explanations for their predictions. Asking for children's explanations for their predictions gave further evidence of the extent of children's knowledge of the connections needed in a circuit, and in some cases insights into their thoughts about why such connections are required. Across the class as a whole, all referred to components—and many talked about the connections needed, drawing on generalisations that could be made from direct observation. In addition, four children offered explanations referring to the path of electricity. The range of explanations children offered showed some similarities to those reported by Asoko (1996), Gutwill, Frederiksen, and Ranney (1996) and Shepardson and Moje (1994), in their studies of older children and adults. In Asoko's study there were children who offered explanations that focused on components—the battery or wires. Explanations referring to connections are widely reported by Shepardson and Moje (1994) and Asoko (1996). Gutwill et al. (1996), in their work with high school students, refer to 'topological perspectives' on the circuit, which focused on circuit details. All three studies give examples of explanations that refer to the circular flow of electricity or current round a circuit. The explanations offered by the few children in this present study that focused on the path for electricity, for example 'the electricity goes round the wires', show the foundations for this kind of explanation for what is happening in a circuit.

As suggested above, these explanations are different in nature. For some, their explanations did not go beyond a description of circuit components. Others focused on generalisations that could be made from direct observation in referring to the connections needed. A small number offered explanations that went beyond what is observable in offering a dynamic view of electricity and considering how it travels in a circuit. Similar kinds of distinction are made by Metz (1991) in her categorisation of children's explanations for moving gears. She refers to three phases in the development of explanations 'the object as explanation', 'connections as explanation', and mechanistic explanations'. Parallels can also be seen with the different kinds of reasoning identified by Driver, Leach, Millar, and Scott (1996) in their studies of young pupils' images of science, *phenomenon-based reasoning*, *relationship-based reasoning*, and *model-based reasoning*. For instance, explanations referring to components, such as the battery or the bulb, showed features of *phenomenon-based reasoning* in the lack of a clear separation between a description of the phenomenon and explanation. Explanations that highlighted the connections needed in a circuit were more characteristic of *relation-based reasoning.* Here distinctions between description and explanation were starting to be recognised. Children were able to identify key factors that would affect the functioning of a device. Finally, the explanations of children who referred to the power of the battery or the path for electricity suggested the beginnings of *model-based reasoning*, in which description and explanation are more clearly distinguished and explanations involve the use of theories or models that go beyond experimental data.

In summary, findings of the present study suggest that young children offer a range of explanations for what is happening in a circuit not dissimilar to some older children or adults. Their explanations are not confined to describing objects and events. Even at a young age there are children who notice patterns and relationships. In addition, some are beginning to talk about mechanisms in offering explanations for phenomena and events. In the case of electricity this involves imagining entities and processes that cannot be observed directly.

Explorations

The opportunities offered in the final part of the interview for children to undertake their own follow-up explorations provided some indication of children's practical competence. The nature of children's explorations and their spontaneously offered comments gave additional insights into their developing thinking. There was some suggestion that the kinds of exploration children undertook were influenced by their developing thinking and practical competence, and in some cases prompted by the interview procedure itself. In a number of cases children talked explicitly about their greater awareness of the connections needed as a result. Features of their explorations and investigations corresponded to those discussed in previous studies of children's self-directed enquiries (Metz, 1998). In the 'wider explorations' undertaken by children who were not yet competent in circuit-making, children adopted a trial-and-error approach in seeking to make the circuits work. Their enquiries had an engineering rather than a scientific structure and a focus shown in an emphasis on trying to get devices to work. For example, Alexandre tried connecting wires to different part of the battery and experimented with different coloured wires in his attempts to get the bulb to light. The strategies employed by the children in this study who tried out particular circuit examples were more focused and suggested a shift from just trying to make something work to seeking to identify the specific connections needed with a tacit assumption that a general conclusion could be drawn, more characteristic of a scientific frame for enquiry. These children were able to make use of both positive and negative examples from practical experience in developing their knowledge about simple circuits. The comments of some of them suggested in addition that they were consciously aware of their views and were testing these out deliberately. This observation is in line with previous studies of young children's enquiry processes (Karmiloff-Smith & Inhelder, 1974; Kuhn, Schauble, & Garcia-Mila, 1992; Schauble, 1990) and with the growing evidence of young children's capabilities and their concern to search for explanations for phenomena and events (Brown et al., 1997).

Relationship between Predictions, Explanations, and Explorations

The range of data collected in the study also provided opportunities to explore the relationship between children's predictions, explanations, and explorations. Findings suggested the relationship is not straightforward. Children with the same levels of practical competence made predictions characteristic of different models of the circuit, offered different views about the connections needed or gave different explanations for what is happening in a circuit. Furthermore, children who made the same predictions provided different types of explanation for their views. The interaction between children's predictions and explanations in electricity was examined by Shephardson and Moje (1994) in their work with older primary children. They highlight the ways in which understanding of circuit connections and flow of charge are connected and influence each other in a positive way. However, they also found that while children may provide more accurate predictions and circuit drawings as a result of teaching, they might still give explanations that contradict a scientific view. These findings from studies of children's predictions and explanations at different ages indicate it is therefore important that assessment techniques focus not just on procedural understanding (how to make circuits) but also probe children's understandings of why such connections are needed. More generally this underlines the value of being able to draw on a variety of evidence in seeking to make sense of children's views. Reliance on one form of evidence can lead to both underestimation and overestimation of children's competence, knowledge, and understanding.

Impact of the Interview Procedure Itself

The interview procedure developed for this study showed some success in eliciting children's views, not always offered spontaneously. Children were keen to offer predictions, and most gave explanations for their views. In addition, there was evidence of children's pro-active approach to the interview process itself. Many took charge of the cards showing photographs of electric circuits and checked their responses were recorded accurately. The approach to data collection and analysis made it possible to track any change or development in children's thinking across the interview. Some children's actions and comments suggested they were becoming more conscious of their own views and reflecting on their thinking in the light of further evidence. The way the interview was constructed may have contributed to this. In asking for predictions and explanations, the interview process prompted children to make their thinking explicit. The circuit examples deliberately exposed children to a range of options, both positive and negative, designed to focus on key features of the circuit. In some cases, discussion of the circuit examples may have acted as an instructive stimulus (Siraj-Blatchford & Siraj-Blatchford, 2002), prompting further development in the final part of the interview. How far the development of children's explorations and thinking may be influenced by the interview procedure itself is a subject for further investigation.

Implications

Findings suggest it is important not to underestimate young children. They add to evidence that from a young age children try to explain phenomena and events and may offer views not dissimilar to some older children or adults. Although young children may lack experience, they are capable of range of forms of reasoning. As found in previous studies of older primary age children (e.g., Smith, diSessa, & Rochelle, 1993, or Smith, Maclin, Houghton, & Hennessey, 2000), there were examples of young children who could think abstractly as well as concretely and search for patterns or causal mechanisms. In early years science curricula there has been a tendency to focus on processes of observing and describing on the grounds that this is developmentally appropriate (Metz, 1995, 2004). This tendency is reflected, for example, in early levels of the National Curriculum (Department for Education and Employment, 1999) or in the Early Learning Goals (QCA, 2000). While observing and describing are relevant and important priorities for learning and teaching with young children, this study reinforces the view that limiting attention to these processes runs the danger of failing to capitalise on young children's capabilities.

There are a number of implications for assessment in electricity. The study offers frameworks for assessing children's developing knowledge and understanding in electricity. Findings underline the importance of using a range of approaches to assessment. They suggest there are complex relationships between practical competence, predictions, and explanations so that reliance on one form of assessment may misrepresent children's knowledge and skills. In early years settings, assessment information is often based on observation of children's talk and actions. However, the responses of children in this study illustrate the value of encouraging children to explain their thoughts and actions. Not only were children able to offer explanations, but their explanations gave insights into their developing thinking.

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Appendix. Categories of explanations offered for predictions: relationships between practical competence, models of the circuit, and explanations (n = 28)

Child	Made circuits successfully	Model	Components	Connections	Power from battery	Path for electricity
Rasheed	Yes	A	6	0	0	0
Aisha	Yes	B	9	0	0	0
Alexandre	No	B	23	1	0	0
Elaben	Yes	B	5	1	0	0
Javid	Yes	B	3	11	0	3
Kingsley	Yes	B	14	2	0	1
Nesha	Yes	B	19	0	0	0
Nita	No	B	6	0	0	0
Raisha	Time	B	23	0	0	0
Sabrina	No	B	9	3	0	0
Joseph	Yes	B/C	7	5	0	0
Kalvin	Time	B/C	11	0	0	0
Anna	Yes	C	15	9	0	0
Cairo	Yes	C	8	11	1	0
Eduardo	Yes	C	17	4	0	0
Motur	Yes	C	7	7	0	0
Omar	Yes	C	8	16	0	0
Sarfaraz	Yes	C	10	10	0	0
Zarah	Yes	C	2	15	0	0
Maruf	Yes	C/D	18	6	0	0
Anil	Yes	C/D/E	9	15	0	0
Basil	Yes	D	5	14	0	0
Benedicta	Yes	E	13	10	0	0
Deji	Yes	E	7	12	0	4
Mariamma	Yes	E	12	10	0	0
Raymond	Yes	E	8	9	0	1
Tara	Yes	E	9	16	0	0
Prima	Yes	F	5	18	0	1

Key: Yes = made device work; Time = took time to make device work; No = could not make device work without help.
Some children gave more than one explanation for some predictions. As a result, the total number of explanations can exceed the number of circuits (24).