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Consistency in pupils´ explanations about combustion.

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ABSTRACT

This paper reports some findings of a study on 14-15 year old pupils´ ideas about combustion. Patterns in pupils´ explanations across a range of questions are described and analysed, in order to gain insight into the consistency or inconsistency of their explanations. Data have been collected by a questionnaire survey which uses mainly open questions, some of which are general questions about combustion and others which use specific examples. Responses have been analysed using systemic netwoks. Categories from networks have been combined to produce patterns of explanations that could be considered as theories. The general characteristics of these theories, the consistency with which they were used, and implications for teaching and learning are discussed.

INTRODUCTION

This paper explores two general conclusions that appear to be implicit in much of the research literature about pupils´ alternative frameworks and the difficulties of promoting more scientific explanations from pupils. These two conclusions are that pupils tend to be inconsistent in their explanations, and the apparently conflicting conclusion that pupils´ alternative frameworks are robust and difficult to change.

Clough and Driver (1986) explored the consistency in the use of pupils´ alternative frameworks across different areas of science. They found that pupils tended to use similar alternative frameworks to one another, but that individuals were not as consistent in their use of alternative frameworks as they were in the use of scientific explanations. Paris (1992), in her study of pupils´ understanding of acids and bases, also found that pupils were more inconsistent in the use of alternative frameworks than scientific explanations. Similarly, in the field of combustion BouJaoude (1991) claims that pupils´ understandings about burning "were fragmented, inconsistent and at variance with scientific knowledge".

On the other hand many researchers have reached the conclusion that pupils´ alternative conceptions are very robust and resistant to change. This appears to contradict the inconsistent use of alternative frameworks. If pupils are willing to shift in their explanations from the use of one alternative framework to another, why are so reluctant to use scientific explanations?.

In this paper pupils´ explanations of combustion are examined to explore whether they use alternative explanations consistently. Where there is apparent inconsistency in pupils´ explanations, three possibilities are explored:

1. The pupils have an underlying rationale for their explanations, which is not immediately apparent to the researcher. It is possible that apparent inconsistency in pupils´ explanations is simply inconsistency when viewed from a scientific perspectiva. Pupils´ explanations may seem consistent when viewed from the pupils´ perspective.
2. The very nature of an alternative theory gives rise to explanations which appear inconsistent from a scientific perspective. The pupils do not see the need for an explanatory theory as powerful as the scientific one, and so are satisfied with less powerful theories which do not take into account some aspects of the phenomenon of combustion.
3. The pupils may be in a state of transition from one theory to another. Their learning may be producing conceptual change in which they are trying to accommodate new ideas.

Black and Simon (1992) talk about pupils´ "theories" and scientists´ theories as being like two islands, and that the teacher´ job is to build bridges between the two islands. From a researcher´s perspective the problem of inconsistency may simply be that we have failed to visit the pupils´ island and have simply viewed it from afar (items 1 and 2 above), or that we are seeing the traffic across the bridges between the islands (item 3).

In this paper the explanations of 150 pupils aged 14 and 15 year, about some aspects of combustion, are studied using a questionnaire. The way in which the underlying theories have been extracted from the elements of their explanations is described, and the possible consistency or inconsistency with which the students apply their ideas is analysed. The results obtained are discussed in terms of the nature of any inconsistency, and the changes that must be brought about to promote more scientific explanations of combustion.

CHARACTERISTICS OF THE EXPLANATIONS OF THE STUDENTS DESCRIBED IN THE LITERATURE

Driver, Guesne, and Tiberghien (1985 (a)) describe a number of general characteristics of the explanations of pupils:

* Explanations are guided by directly observable characteristics of the situation and what is not perceptible is ignored.
* Pupils have a limited focus, that is manifested in:
  (a) a tendency to interpret the phenomena in relation to the absolute properties or qualities of objects instead of considering the interaction between the elements of a system.
  (b) a tendency to focus on changes and not on the state of equilibrium. For example, if there is no movement there is no force; or gases exert pressure only when they move.
* Pupils use linear causal reasoning, and do not consider all the relevant variables in the problem and relationships between them.
* Pupils do not differentiate clearly between different concepts (e.g. heating and burning). Similarly their use of language is also less precise than that of scientists. Pupils often use the same word to mean many things. On the other hand students use many words to mean the same thing.
* Pupils´ explanations are context dependent: different ways of explaining are often used for different situations which are examples of the same phenomenon.

Andersson (1986(a)) describes the nature of pupils´ causal reasoning. He claims the existence of a common core in students' explanations and predictions about many different phenomena, which he calls the "experiential gestalt of causation". The experiential gestalt of causation starts to be built by an individual at a very early age and is based on the simple experience of children. In essence, an agent exists (that can be a child or an instrument) whose direct or indirect action affects an object producing a type of change. The essential elements are *agent-instrument-object*.

Gutierrez & Ogborn (1992) used the model of Kleer and Brown as a more developed causal framework for analysing alternative conceptions. This description of what is involved in causal reasoning contains five basic elements: 1) device topology: a representation of the structure of the physical system; 2) envisioning: working out from the structure how the system could work; 3) causal model: the result of envisioning; 4) running: inmagining what the causal model would do and 5) episodes: divisions of time within which the explanation stays the same.

Gutierrez et al. say that an acceptable explanatory model, when run, must satisfy the constraints of *consistency*, which requires that the model does not suffer internal contradictions, *correspondence*, which requires that the model predicts what actually happen, and *robustness*, which requires that the model continues to correspond to the facts when the context is modified to another similar one.

Ogborn and Bliss (1990) in their paper " A psychologic of motion" use similar reasoning to explain how pupils´ "common sense ideas" of motion are developed by children through interaction with their immediate environment, to produce logically consistent explanations of motion. The explanations take the form of causal schemes which become successively more elaborated as a child developes. A conclusion from all these papers about the type of reasoning used by pupils is that, although it is not scientific, it is internally consistent when viewed from the perspective of the pupils.

A possible explanation for the pupils´ alternative frameworks being different in nature from scientists´ explanations, is that pupils are limited by their stage of genetic epistemological development. Pozo, Puy and Sanz, (1992) compare pupils´ "theories" with scientific theories. Scientific theories are explicit, coherent, general, deductive, are based on a complex multiple causality and are looking for the truth. Those of the pupils are: implicits, incoherents, specific, inductive, are based on the simple linear causality and are looking for usefulness in everyday life. These authors relate some structural characteristics of students' implicit theories, that are different from the scientific theories, to the level of cognitive development of pupils, and in particular to the lack of development of formal thought in the pupils. Certain characteristics of pupils´ theories act as actual epistemologic obstructions that must be overcome: they are one-way (agent-object) linear causality; wrong strategies of quantification or no quantification at all (qualitative description); transformations without conservation, or focusing on what is transformed but not in what is conserved.

In analyses of the types of explanations given by pupils in different areas of physics, Monk (1990, 1991) has compared the proportions of pupils´ at different ages giving different types of alternative explanations and scientific explanations, with the proportions of pupils at the same ages who would be expected to be a certain levels of genetic epistemological development. The similarity between figures is striking lending support to claims (Monk, 1990) that:

> "(i) there is a genetic epistemological stage related ceiling to the cognitive processing on the part of pupils;
> (ii) pupils can benefit from tuition such that their performance on test items can be increased to the limit set by their then current stage of genetic epistemological development".

Similarly Eckstein and Shemesh (1993) have developed a mathematical model to describe the pattern in proportions of pupils of different ages giving different types of alternative and scientific explanations of motion. The mathematical model also applies to the level of genetic epistemological development of pupils, and again implies that the type of explanation given by pupils is controlled by their level of cognitive development.

Chi, Slotta and Leeuw (1992), and Chi (in press) propose a different explanation of pupils´ alternative conceptions, and the difficulties of changing pupils´ conceptions to more scientific ones. They propose that knowledge can be divided into various distinct ontological categories. The three major ontological categories are matter, events and abstractions. Entities which are categorised into one ontological category have certain attributes that differentiate it from other ontological categories. Reiner, Chi and Resnick (1988) give many examples from physics where pupils have incorrectly categorised scientific processes (constraint-based events) as materials. This lead to considerable difficulties for pupils in developing scientific concepts. For example, the process of "heating" may be classified incorrectly as a substantialised material "heat". Heating is a process which has properties such as happening during a particular time, and being caused by certain interactions, whereas heat can be gained or lost, can travel along a metal bar, or can be lost during burning and account for the weight loss in many burning processes. Chi, (in press) argues that conceptual change within an ontological category (non-radical conceptual change) is much easier than conceptual change across ontological categories (radical conceptual change), and that indeed, conceptual change across ontological categories is "nearly impossible to acomplish". "There are no concrete operations that can transform a physical object such as a cup, into an ontological different entity, such as a dream. Likewise, there is no psychological learning mechanism that can modify a concept from one ontological category into another. No mechanism of addition, deletion, generalization, discrimination, specialization, proceduralization and so forth can change the meaning of a concept from one ontological category to another..." . It is suggested that the radical conceptual change needed to develop a concept in a different ontological category, may take place by developing a new concept within the correct ontological category, which may coexist with the old concept in the incorrect ontological category.

The division of conceptual change into two types helps to solve some of the contradictions in the literature between researchers such as Lawson (1988) who maintains that many biological concepts are acquired through a process of accretion, and other authors who have found pupils´ alternative conceptions robust and difficult to change. The former is classified as conceptual change within an ontological category (non-radical conceptual change) and the latter across ontological categories (radical conceptual change). It also gives some insight into the issue of consistency or inconsistency of pupils´ explanations. Pupils´ explanations of concepts or "entities" within an ontological category may well be consistent but pupils may draw on concepts from different ontological categories (e.g. "heat" and "heating") to answer different questions, which to the scientist appear to be about the same concept. From the pupil´s perspective the answers could be consistent, but not so from the scientists´ perspective.

MODELS OF PUPILS´ UNDERSTANDING OF COMBUSTION IN THE LITERATURE

A number of studies have been carried out which have attempted to synthesise findings about pupils´ explanations of combustion by applying general criteria to classify the responses to a variety of questions (Andersson, 1986 (b); Andersson, 1990; Meheut, Saltiel, and Tiberghien, 1985; Meheut, 1982; Pfundt, 1981; Prieto, Watson and Dillon, 1992).

Andersson (1990) describes a categorisation system which can be applied to pupils responses to a variety of questions concerning both chemical and physical change. The categories are (a) disappearance, (b) displacement, (c) modification, (d) transmutation and (c) chemical interaction. These are illustrated as follows:

(a) Disappearance
When asked about the weight of exhaust gases produced when petrol is burnt in a car (Andersson & Renstrom, 1983) some pupils answer that some of the petrol is used up in the car and disappears.
(b) Displacement
An example is of pupils explaining the disappearance of water from a puddle on the floor, by saying that the water had penetrated the floor, i.e. it had been displaced to a different place.
(c) Modification
Meheut et al. (1985) give examples of pupils explaining the burning of alcohol and the boiling of water in terms of modification of liquid alcohol to alcohol vapour and liquid water to steam.
(d) Transmutation
Some changes are described in terms of transmutation of substance into energy, of energy into substance or of one substance into a new one, for example iron wool being transmuted into carbon during combustion.
(e) Chemical change
Ideas of chemical change are applied correctly to examples such as petrol burning, but also incorrectly to physical changes (Osborne & Cosgrove, 1983). Some pupils think that the bubbles of steam are oxygen and hydrogen gases.

Meheut et al. (1985) developed a way of categorising the responses of students (aged 11-12) based on their ideas of conservation. There are some similarities with Andersson's categorisation scheme but Meheut et al. also incorporate the nature of the combustible material in the categorisation system. Pupils responses can be divided into two groups according to the nature of the combustible substance. The first group includes responses about metals, wax, water, and alcohol, which are said to melt or evaporate, rather than burn, or using Andersson's terminology, are modified. The second group includes responses about wood, cardboard, paper, alcohol and air, which are seen to burn and be changed into another substance or nothing. Using Andersson's categories, these substances disappear or are transmuted. An important feature in the categorisation of Meheut et al. is that during transmutation each substance is transmuted separately. Students often fail to realise that matter is interacting.

The role of oxygen and air is not dealt with adequately in either Andersson's or Meheut's model. One difficulty in interpreting responses to questions designed to elicit students understandings of the role of oxygen and air in combustion is that not all students have a good understanding of the nature of air (Russel et al., 1991; Brooks & Driver, 1989). Brooks and Driver reported that even at age 16 about three quarters of pupils thought that air had zero or negative weight. Pupils may, therefore, conserve matter in their explanations of chemical reactions, but not necessarily conserve mass.

In an earlier paper (Prieto, Watson and Dillon ,1992), we described how the categories of Andersson and of Meheut were developed to produce operational definitions of three categories of pupils´ explanations of combustion, to fit our data. The categories were Modification, Transmutation and Chemical Reaction. The Disappearance category of Andersson is subsumed under transmutation and examples of Displacement were not found in our data. The three categories are defined in table 1.

TABLE 1

OPERATIONAL DEFINITIONS OF PUPILS' EXPLANATIONS

1. Role of oxygen/ interaction

C:

C1: Pupils recognise that the combustible substance and oxygen/air interact.

C2:The reaction is irreversible.

T:

T1:There is no interaction between the combustible substance and the oxygen/air.

T2: Oxygen/air may or may not be recognised as necessary for combustion to take place.
T3:Burning is a destructive process.
T4: The destructive process may release or liberate substances from the combustible substance.
T5: Burning is irreversible.

M:
M1:Oxygen/air is not involved in the change.
M2: The change is reversible.

2. Flame/ fire

C:
C3:Energy changes may be observed but are not explained.
C4: The flame/fire is evidence of a chemical reaction.
C5:The flame contains both the combustible substance and oxygen/air reacting.

T:
T6:The flame/fire is an active agent of change.
T7: Air/oxygen may be needed to 'feed the flame' or 'keep it alive'.
T8: Air/oxygen is transmuted by the flame/fire or is consumed by it.
T9: Matter may be transmuted into heat.
T10: Flames contain only the combustible substance or oxygen/air or possibly both but with no interaction.

M:
M3: The flame/fire is a source of heat to make the modification occur.

3. Products and reactants

C:
C6:The products contain the reactants in a different chemical combination.
C7: Mass is conserved provided that pupils think that gases weigh something or gas is not 'lost' to the atmosphere.
C8: Properties are not conserved.

T:
T11: Substance is changed from one substance to another or into nothing during combustion.

T12: Oxygen/air may be transmuted separately into a product.
T13: Oxygen may be needed but does not interact in a chemical sense.
T14: Mass may increase, decrease or stay the same (because the transmuted products are different from the reactants).
T15: Properties are not conserved.
T16: Properties may be substantialised and therefore be involved in the transmutation.

M:
M4: One substance changes to a different form of the same substance.
M5: Substance is conserved.
M6: Mass may be conserved, but this depends on whether different forms of the same substance are considered to weigh the same.
M7: Some properties are conserved.

It can be seen that the two alternative frameworks "Transmutation" and "Modification" share many of the characteristics of pupils alternative explanations described in the literature reviewed earlier. The alternative frameworks fit the descriptions in the following ways:

* There is a heavy dependence on immediately observable characteristics of combustion (Driver et al. 1985(a)). Oxygen or air, which cannot be seen, play no role in interacting with the combustible substance in Transmutation (T1, T2, T7, T8, T12 and T13). and plays no role in Modification at all (M1). Gaseous products and weight changes are unimportant in Transmutation (T14) and Modification (M3) explanations and receive little attention from the pupils.
* The limited focus of the two alternative explanations can be seen in the mainly descriptive nature that they share (Driver et al. 1985(a)). The explanations have predictive validity, in that they allow pupils to predict what changes will occur in what they perceive as similar circumstances, but they fail to go beyond the inmediately perceptible. As predictive explanations Transmutation functions well on the types of examples of materials that pupils normaly give as examples of burning, i.e. carbon/hydrogen based materials such as wood, paper, plastic, cloth and living things. Modification functions well on examples of burning that pupils incorrectly perceive as similar to changes of state such as a candle or a metal burning (melting) and alcohol

burning (evaporation); under not too close scrutiny the original substance reforms after burning as a solid product (freezing) or as a liquid (drops smelling of alcohol condensing on a cold surface from an alcohol frame).

* Linear causal reasoning is used in both cases (Driver et al. 1985(a); Andersson, 1986(a)). In Transmutation the flame or fire is an active agent of change, which acts on the combustible material, and perhaps the oxygen separately, in a destructive process to produce a product which is completely different from the reactant(s) (T3, T5, T6, T11, T12, T14, T15). In Modification the heat or fire acts on the combustible substance (M4) to change it into a different version of the same substance (M4, M5, M6, M7).

*Both Transmutation and Modification can be categorised into the same ontological category (Chi, in press) as Chemical reaction, i.e, the "constraint based events" category, but the concept of heat/heating which is used within the Transmutation explanation, is classified incorrectly by some pupils. Some pupils substantialise heat (T9), i.e. categorise it as a "matter" instead of as a "constraint-based event".

* The imprecise use of concepts and language (Driver et al. 1985(a)) is very evident in the pupils´ responses, but less evident in the operational definitions above which try to avoid ambiguity. Nevertheless the evident confusion between the concepts of burning and heating are obvious in the Modification explanation.

* The mental modelling of combustion as "Transmutation" or as "Modification" requires only concrete operational thinking as compared with "Chemical Reaction" which requires formal operational thinking (Monk 1990, 1991), and this may explain the low number of pupils who give "Chemical Reation" explanations. The mental modelling of combustion as Modification involves the reversible transformation of a substance with certain properties (e.g. solid properties) into the same substance with some different properties (e.g. liquid properties) and is characteristic of early concrete operational thinking. Combustion as Transmutation involves an increase of the product at the expenses of the combustible substance; i.e. the system contains only two components which are polar opposites on the same scale: less combustible substance, more product. This is characteristic of late concrete operational thinking. In mentally modelling combustion as Chemical Reaction, the thinker must have a model that contains at least three components (i.e. combustible substance,

oxygen and product), and the relative ratios of these co-vary in a direct and indirect fashion. This could be interpret as requiring the compensatory thinking that is one of the characteristics of formal operational thought.

RESEARCH METHODS

A questionnaire, which contained nine questions, all of them open and one also containing a fixed response item, was developed through a series of four pilot studies which involved about 150 pupils in Spain and England. The main foci of the questionnaire were: the process; the products, including aspects of conservation; and the examples of combustion that pupils give. The questions which are the focus of this paper are given in appendix 1. This paper analyses data from 150 spanish students aged 14 and 15. This number allows pupils with similar types of explanations to be grouped together. This age was chosen as all the pupils would have studied some elementary chemistry including combustion. The pupils were selected from schools to give a sample which was representative of the population at that age.

The responses to the questionnaire were analysed as described below:

1. The responses were analysed by developing systemic networks (Bliss, Monk and Ogborn, 1983) to capture the meanings of the responses in a systematic way.
2. The networks were analysed to identify indicators of different categories of thinking, and these indicators were used to modify Andersson´s (1990) categories and to generate the detailed descriptions of different categories of thinking, given in table 1 (Prieto et al., 1992).
3. The detailed descriptions were used to categorise pupils´ responses question by question.
4. The consistency of pupils´ use of different explanatory models was examined, and the pupils were divided into different groups according to the consistency of their responses.
5. A detailed qualitative analysis of the responses of pupils in the different groups was carried out to examine the nature of consistency/inconsistency of each group.

RESULTS

Developing systemic networks.

The first stage in the analysis of the data was to develop systemic networks, to capture the essence of the responses to open questions, in a way that allowed aspects of the responses to be quantified. An example of a network is given by the one for question 1(a) and (b) shown in figure 1. The examples of pupils´ responses given below show how responses are encoded.

Pupil 70

1a): "It is a combustion process that happens to a substance. It goes from a state to another, e.g. a leave is transformed into ashes, from liquid to gas". 1b): "It evaporates".

This answer has been coded as follow:

"It is a combustion process that happens to a substance": 1.11
"It goes from a state to another, e.g. a leave is transformed into ashes": 1.36
"from liquid to gas. 1b) It evaporates": 1.41

Pupil 32

1a): "It is a chemical reaction that happens when a substance gains such high temperature that it cannot stand it". 1b): "Changes to another substance".

This answer has been coded as follow:

"It is a chemical reaction": 1.12
"that happens when a substance gains such high temperature that it cannot stand it": 2.5
"Changes to another substance": 1.32

Figure 1. Network for question 1 (a& b).

			N	Code
Nature of change	Chemical	Combustion	11	1.11
		Chemical Reaction	5	1.12
		Chemical Change	1	1.13
	Synonimous	- Its burns	88	1.20
	Changes to something different	- Comp. with oxygen	1	1.31
		- Another substance	15	1.32
		- Gas	5	1.33
		- Carbon Dioxide	1	1.34
		- Smoke	2	1.35
		- Ash	65	1.36
		- Carbon	10	1.37
	Changes no necessarily to something different	- Evaporates	5	1.41
		- Melts	7	1.42
		- Turns to powder	1	1.43
		- Changes colour	5	1.44
		- Gets hot	5	1.45
		- Expands	3	1.46
		- Changes form	8	1.47
		- Changes state	6	1.48
		- Changes appearance	1	1.49
	Deteriorates	- Is destroyed	3	1.51
		- Is decomposed	10	1.52
		- Loses properties	2	1.53
		- Becomes less	3	1.54
		- Deteriorates	3	1.55
	Disappears	- Is used up	6	1.61
		- Disappears	14	1.62
		- Disintegrates	15	1.63
Requirements		- Combustible material	12	2.1
		- Oxygen	4	2.2
		- Air	2	2.3
		- High temperatures	3	2.4
		- Heat	5	2.5
		- Fire	49	2.6
		- Other substances	1	2.7
Something is liberated		-Heat	10	3.1
		-Energy	2	3.2
		-Fire	17	3.3
		-Combustible substance	1	3.4
		-Smoke	5	3.5
		-Light	3	3.6

Some of the codes are more useful than others in gaining insight into the pupil´s thinking. The clause “It is a chemical reaction” (pupil 32) could be taken to indicate an understanding that one chemical is seen to be reacting with another. This meaning is not, however, clear from the rest of the response. Similarly “It a combustion process” (pupil 70) could be taken to mean the reaction of a combustible substance with oxygen. The rest of the response shows clearly that this is not the case with a change of state being given as an example of combustion.

Developing operational definitions.

The second stage in the analysis did in fact restore some of the data lost in the coding on the networks. The codes generated in the networks were used selectively to generate the operational definitions of pupils´ explanations given in table 1. The pupils´ responses were then re-examined in the light of the operational definitions to allocate each response to a category of pupils´ explanations.

One difficulty in allocating responses to a category of pupils´ explanations was that it was often difficult to decide whether a response should be categorised as Transmutation (T) or Chemical Reaction (CR). The response given for pupil 32 above is an example of this. The use of the words “Chemical reaction” may be an indication of CR but this is ambiguous. There is a mention of change to another substance but no mention of oxygen or air. This response has, therefore been categorised as intermediate between CR and T as X. Other responses are not ambiguous but contain aspects of both CR and T explanations. These have been also classified as X.

Sometimes pupils give, in different parts of their responses, both Modification explanations and Transmutation/Chemical Reaction explanations, e.g. pupil 70 above. Such responses received a double classification, X and M in the case of pupil 70; T and M in the case below:

Pupil 3

> 1a): "Is when a substance burns", 1b): "It becomes ashes or a different thing happens to it. For example, if it is wood it turns into ash and if it is plastic it melts" .

In spite of these difficulties in interpretation, the operational definitions have allowed a high degree of reliability to be achieved in allocating responses to particular categories of explanations. A 10% sample was coded by two independent coders and 94% reliability between coders was achieved.

Some Interesting examples of responses for each of the categories of explanation are given below:

Chemical Reaction

There are few responses which can be classified as CR.

Pupil 72

9: "c) Because the magnesium with the oxygen make some kind of mixture which weighs more".

Intermediate

The two examples below show pupils who are starting to take into account the interaction between the combustible substance and oxygen. The second student´s use of words as "combustion" and " "reaction" indicates some progress in the use of scientific language.

Pupil 51,

1a): "Is the change that happens to a body when it is contact with the oxygen", 1b): "Usually give off fumes and gets smaller and smaller"

Pupil 102.

1a): "Is a kind of combustion that needs the presence of oxygen to react with and produce fire", 1b): "It is decomposed and is converted into ash"

Transmutation

Pupils using this type of explanations are usually aware of the requirement of oxygen in burning but do not see it as interacting with the combustible substance. Sometimes they see it as necessary to feed the fire or the flame

Pupil 79

6b& c): "There is no oxygen, the fire has absorbed it."

Pupil 80

6b& c): "...the candle is absorbing the oxygen to feed the flame..."

Modification

Pupils using Modification explanations, in spite of the fact that they are conserving the substance, appear to have little understanding of conservation of weight. Weight is often seen as being dependent on the form of the substance with solids, powders, liquids and gases having different weights.

Pupil 50

9: "e) It couldn't increase because it changed into powder and powder does not weigh anything".

They also sometimes substantialise heat or energy: absorbing heat may make a material heavier:

Pupil 35

9: "I have chosen d) because I think that in getting heat the material can in some way increase its weight".

Pupil 46

9: "d) Heat of the flame makes it get heavier"

CLASSIFICATION OF RESPONSES TO EACH QUESTION.

The allocation of answers to categories is shown in table 2.

Table 2. Allocation of answers to categories (n = 150).

	Q1(a&b)	Q5	Q6a)	Q6(b&c)	Q7	Q9
CR	2	1	1	1	6	43
X	10	2	17	24	14	3
T	106	140	20	95	73	40
T + M	13	0	2	0	0	1
M	3	0	65	10	1	21
No code	16	5	3	11	9	28
Blank	0	2	42	9	47	14

The patterns that can be seen in the table are:

* Transmutation was the most commonly used type of explanation in questions 1, 5, 6(b&c) and 7.

* Modification is only important in the case of the candle (Q6) and to some extend the magnesium (Q9).
* The scientific theory Chemical Reaction is little used but some pupils use some elements of it (X).

The extend to which pupils used one or more types of explanations is indicated in table 3.

Table 3. Combinations of different types of explanations used by pupils (%, n = 150).

	(M)	No (M)	Total
(CR) and/or (X) + (T)	box 1 28	box 2 22	50
(T)	box 3 34	box 4 16	50
Total	62	38	100

All pupils used a Transmutation type of explanation on at least one occasion, and 16% of pupils (box 4) use only Transmutation explanations. About two thirds of the pupils (boxes 1 and 3) use Modification explanations, although most of these (50% of the total sample) use Modification explanations only once. Half of the pupils gave at least one response that indicated some understanding of a chemical reaction (boxes 1 and 2, CR or X), but all of these pupils also used Transmutation explanations, and usually this kind of explanation was used more often.

In the next section the responses of pupils are considered in more detail in order to shed light on whether the pupils were responding in a consistent or inconsistent way.

CONSISTENCY AND INCONSISTENCY IN PUPILS´ RESPONSES.

The simplest group to consider is the group of pupils in box 4 in table 3 (16%) who are clearly consistent in their responses, using only one type of explanation. An example of a pupil who consistently used Transmutation explanations is given below:

Pupil 62

1a): "What I understand by burning is when a material is able to produce heat with another material which helps it to produce flames". 1b): "It consumed".

5: "You get ashes and residue".

6a): "Wax has been consumed and the flame has been extinguished because of lack of oxygen".

6b&c): "The air has been consumed and there is no supply of oxygen.

7: "It is made of different parts of heat with different intensities".

9: "Because a material as burns it disappears and all that is left is a powder that weighs less than in its original state".

Use or non-use of Modification explanations.

No pupils used only Modification types of explanations. Modification is always used in combination with a different kind of explanation (boxes 1 and 3, in table 3). From a scientist´s perspective pupils are being inconsistent. From a pupil´s perspective they may in fact not be so. Their lack of precision in the use of language, their lack of development of certain concepts, and their lack of discrimination between concepts, allows them to use these explanations withouth problems.

Some of the apparent inconsistency arises from the lack of development of appropiate scientific language in the pupils and the corresponding lack of development of certain concepts. Pupils sometimes fail to distinguish between heating and burning:

Pupil 11,

1a): "Is something that happens when the material is at such a high temperature that it can not stand it and a spark jumps out and then it begins to burn. If we are talking about metals, they do not burn, they melt".

In this response burning is taken to mean both burning and heating. Melting of metals is elicited in response to a question about burning, not heating, and then cited as an example of something that does not burn. This lack of precision in the use of language may in fact reflect an underlying lack of development of the concepts of burning and heating.

Similarly burning and heating are confused by some pupils in response to question 9, which is about the burning of magnesium. Two kinds of Modification explanation are given: "Magnesium" when heated expanded so that it weigh more" and what pupil 113 says:

Pupil 113

9: "e) If you burn magnesium it will weight the same, it is like heating a litre of water, at the end you have a litre of water but vapour".

This confusion between heating and burning allows pupils to give explanations of burning, of a Modification type, when they understand "burning" to mean "heating". This type of explanation can coexist with explanations in which a more conventional understanding of the word burning is used.

A related problem is that pupils fail to distinguish between combustion and change of state. An example is pupil 3 (seen before): 1a): "Is when a substance burns", 1b): "It becomes ashes or a different thing hapens to it. For example, if it is wood it turns into ash and if it is plastic it melts" .

In many ways perceptions about burning alcohol and boiling water over a bunsen burner are similar: a flame is seen, heat can be felt, the volume of liquid gets less and a vapour is formed. There are also similarities between burning wax in a candle and melting a block of ice. In this case the concepts of change of state, and burning, are not well developed and become confused, because the pupils do not use adequate criteria to distinguish between them.

A factor which appears to control which type of explanation is the nature of the combustible material. The present study confirms the results of Meheut et al. (1985) in showing a greater tendency to use Modification explanations with wax and metal. There is, however, insufficient data in the present study to show whether pupils discriminate between different combustible substances in a consistent way: there are too few different types of combustible material included in the study.

There are a number of studies in the literature in which Modification explanations can be indentified in pupils´ responses. There are indications from the literature that this type of explanations, as well as being dependent of the nature of the material being burnt, is also age dependent, with its use decreasing with age. Some results are summarised below in table 4. If students say that the substance melts or evaporates on heating/burning, or if the author maintains that the students consider that the indentity of the substance has been conserved, this has been taken as an indicator of the Modification category.

Caution is needed in interpreting tha data presented in table 4, because they are few studies and because the questions used to elicit the responses, and the way that they have been asked varies from study to study. Nevertheless it appears that the use of this type of explanation does decrease writh age. Presumably as pupils use of language develops and as their undestanding of the concepts involved in combustion becomes more sophisticated, they form a more generalised view of combustion, in which they distinguish burning from heating, and combustion from change of state.

Table 4. Use of Modification model.

Study	Age	Sample size	Substance	% Using Modification
Metals				
Meheut et al. (1985).	11-12	102	iron	82-88
Sanmarti (1989)	13	54	copper	46
This study	14-15	150	magnesium	18
Sanmarti (1989	18-19	59	copper	12
Wax				
Meheut et al. (1985)	11-12	102	candle wax	82-97
BouJaoude (1991)	12-13	20	candle wax	60
This study	14-15	150	candle wax	43

Use of Chemical Reaction, Intermediate and Transmutation explanations.

50% of the pupils give responses which include Transmutation explanations as well as explanations that indicate some aspects of Chemical reaction or Intermediate explanations (boxes 1 and 2 in table 3). Most of these pupils seem to be using Transmutation explanations most of the time, but at the same time are beginning to incorporate aspects of Chemical Reaction explanations in their responses. An example is given with pupil 64:

Pupil 64:

1a): "Something burns when it has got fire". 1b): "Depending on the substance, a grey or black powdered substance remains".

5: "You destroy it".

6a): "If the candle is small it is consumed. If the candle is big, the oxygen is consumed before".

6b&c): "The oxygen is being consumed and the container is full of carbon dioxide".

7: " Of gunpowder that as it is burning releases nitrogen".

9: "c)". No explanation.

This pupil choses the correct option for question 9, which explains an increase in weight of magnesium by its reaction with oxygen. The idea of interaction is not so clear in response to question 6: the candle is consumed and the oxygen is consumed and replaced by carbon dioxide, but it is not clear whether these are two independent processes of Transmutation or whether there is chemical interaction between the two substances. The responses to questions 1 and 5 are Transmutation with the combustible substance being transmuted to a destruction product. When asked about the role of oxygen in combustion this pupil, therefore, can choose the correct option in a multiple choice question (Q9), has difficulty in articulating the role of the oxygen in an open format question asking about the oxygen (Q6) and fails to consider oxygen in the other questions where he is not specifically asked about it. It appears that this pupil is struggling to incorporate the role of oxygen into a Transmutation model, which did not previous take oxygen into account.

Two more examples which show similar efforts to incorporate oxygen into a Transmutation model are:

Pupil 51

1a): "It is a change which occurs to a body in contact with oxygen". 1b): "Normally smoke is evolved and it gets less every time".

Pupil 102

1a): "Is a form of combustion which requires the presence of oxygen to be able to react with and produce fire". 1b): "It decomposes and is converted to ashes".

Pupil 138 below uses ideas of interaction but this time the interaction is between air and the flame:

Student 138:

6a): *blank*

6b&c): "The air is absorbed by the flame and when the air has finished the flame goes out"

7: "Oxygen and materials from the match".

The pupil has incorporated ideas of interaction into a Transmutation model by viewing oxygen/ air as necessary to interact with the active agent of change, the flame, in order to allow burning to take place. A similar explanation of the role of oxygen is given by pupil 79:

Pupil 79:

6b&c): "There is no oxygen, the fire has absorbed it".

In some pupils there seems to be some progression towards the Chemical Reaction explanation in term of the language used. Some pupils incorporate scientific language such as combustible, chemical reaction, combustion, into what are essentially Transmutation responses:

Pupil 95

1a): "A chemical reaction where there are a “combustible", air and something that consumes the combustible, fire in this case, and ashes is the substance that is left from this reaction, it is what remains”. 1b): "Become ashes".

5: "You get ashes which is the result of the chemical reaction from wood and fire".

6a): *blank*

6b&c): "As the place is close there is a combustion with little amount of combustible (air) and as it is finished the fire goes out".

7: "Fire".

9: "e) Because the magnesium has been burnt and the rest of the gases that are produced by the fire are taking off weight".

It therefore appears that the pupils in boxes 1 and 2 in table 3 are inconsistent in their use of explanatory models. Some of the inconsistency does not, however, arise from illogical or ad hoc thinking, but from a struggle to come to terms with two mutually exclusive explanatory models. It can be seen that some of the pupils explanations are attempts to introduce new ideas from the Chemical Reaction model into a Transmutation model. It appears that for other pupils the kind of explanatory model used depends on the context of the question and the way it is formulated. Perhaps some pupils have more than one explanatory model for combustion in their memories, and call up for different models to use in different circumstances.

DISCUSSION

In this section the nature of the conceptual change which pupils must undergo and implications for teaching are discussed. An examination of pupils´ explanations (see table 1) reveals that certain aspects which are normally presented in scientists´ explanations of chemical change are completely absent:

* Pupils fail to mention imperceptible products such as gases. Even pupils who talk about the combustible substance interacting with oxygen, usually talk about an ash as the product and fail to mention gaseous products. Oxygen is rarely mentioned spontaneously: pupils usually only mention oxygen in response to direct questions about its role.
* The weight of reactants and products, although playing an important role in scientists´ explanations, has a minor role in pupils´ explanations. This is not surprising as many pupils of the age of pupils in this study fail to realise that gases have weight, or even think that they have a negative weight (Brooks and Driver, 1989; Stavy and Satchel, 1985). This precludes even pupils with a reasonable understanding of chemical reactions from drawing conclusions from measurements of weight. For pupils using Transmutation explanations there is no necessity for a product to weigh more, the same o less than the reactant, because it simply becomes a different substance.
* Pupils make no mention of atomic or molecular particles. This could explain why attempts to change pupils conceptions by teaching about particles have failed (e.g. Meheut et al. 1985). The pupils may see no relation between their explanations and explanations in terms or particles.

A comparison of the Modification explanation with the Chemical Reaction explanation (table 1) reveals the following differences: In Modification there is no role for oxygen (M1), the process is reversible (M2), the flame/fire is the source of heat to make the modification occur (M3) and the product is the same substance as the reactant (M4, M5, M7). In chemical reaction oxygen interacts with the combustible substance (C1), the process is irreversible (C2), the flame/fire is evidence of a chemical reaction (C4) and the product or products are a different substance from the reactants (C6, C8).

Of the pupils´ models presented in this paper, Modification is the most primitive model:

* It requires the lowest level of cognitive processing.
* It depends on selective and inaccurate observation: Modification can only be maintained for candle wax if the candle is observed burning for a limited time, so that the disappearance of the wax is not apparent.
* It explains the most limited range of observations: for example it does not explain the role of oxygen, whereas Transmutation can explain oxygen as being transmuted separately, or as being needed to "feed" the active agent of change, the flame.

The fact, that Modification explanation coexist with Transmutation or Chemical Reaction explanations, indicates that pupils are not limited to this model because of limitations in their cognitive processing power (c.f. Monk 1990, 1991). Nevertheless, pupils have to shift from a model, which involves linear causal reasoning, to one that involves the interaction of two chemicals to form at least one product, often more. The modification explanation, like Chemical Reaction, falls into the ontological category of explaining a "constraint-based event" (Chi, in press).

In order to bring about the conceptual change require, pupils have to learn to distinguish between heating and burning, and to distinguish between burning and change of state. The comparison of the types of pupils´ explanations discussed above suggests that practical exercises need to be constructed in which pupils carefully compare heating, as a process in which heat is supplied from an external source, with burning, in which heat is evolved from the reactants. Similarly change of state from solid to liquid, or from liquid to gas must be compared with combustion. This comparison suggests that more atenttion needs to be paid to comparing the products of the reaction with the reactant and with the products of a physical change in order to perceive the differences. It appears that relying on visually obvious attributes of reactant and products is insufficient for many pupils, for them to realise whether the process is reversible on cooling.

A similar comparison of Transmutation and Chemical Reaction explanations reveals that the differences between these two models are much more subtle and that the conceptual changes needed to move from Transmutation explanations to a Chemical Reaction explanation could be more difficult to achieve. In the Transmutation model burning is a destructive process (T4) in which the combustible substance, and oxygen if it is mentioned, are transmuted separately (T1, T2) into separate products (T11, T12). The role of oxygen is unclear (T2) but it sometimes seen as interacting with or feeding the flame (T7, T8, T10). The flame/fire is the active agent of change (T6), and heat may be substantialised so that matter can be transmuted into heat and vice-versa (T9). The product of combustion of the combustible substance is a different substance from the reactant and so has different properties (T11) and it may weigh less, the same, or more than the reactant. In the Chemical Reaction model, oxygen interacts with the combustible substance to produce products which contain the combustible substance and oxygen in a different chemical combination (C1, C6), and therefore the products weigh more than the combustible substance, as long as pupils understand that gases weigh something and include gases lost to the atmosphere (C7). The role of the energy changes is unclear (C3, C4). The products have different properties from the reactants (C8).

It can be seen that is quite difficult to establish clear criteria for differenciate between the two models through experimentation. Both models can explain what happens to the oxygen, although the Transmutation model´s explanation of why it is needed is weaker: it needed by the flame. Both models can explain the role of heat. Weight changes are often used to reinforce the scientists´ view of combustion. Copper can be heated in a tube connected to gas syringes containing air and the increase in mass of the copper explained in terms of the decrease in volume of the air, This experiment which seems so persuasive to a chemistry teacher can seem rather strange to a pupil who believes that air has no, or negative weight. The transmutation explanation is quite simple: the copper has been transmuted to carbon, which being a different substance has a different weight, or possibly because it contains heat, has an increased weight; the oxigen has been transmuted to nothing.

Transmutation model can be used to explain many everyday observations of combustion. One reason for its persistence may be that it is a simple model which requires a lower level of cognitive processing than Chemical Reaction model. Many pupils have yet to reach the stage of cognitive development that will allow them to use the sophisticated model (Monk 1990, 1991), and change from using linear causal reasoning to using a model that involves the interaction of two chemicals to form at least one product, often more. Another explanation of the persistence of the Transmutation model could be the fact that although like the Chemical Reaction model it falls into the ontological category of explaining a "constraint-based event" certain concepts, i.e. heat/heating, embodied in the model are wrongly classified as materials instead of constraint-based events. In order for this concept to be placed in the correct ontological category radical conceptual change (Chi, in press) must take place.

The explanatory power of the Transmutation model and the Chemical Reaction model is similar for explaining the phenomena included in the models. It is only when aspects that are not included in the model are emphasised that the Transmutation model start to fail, (rol of gases, quantitative aspects including weight and volume changes). The Transmutation model as an explanation of a destructive process works well with carbon/hydrogen based substances, but is less satisfactory in explaining the combustion of metals and non-metals, where there is more substance after burning and where a greater variety of products is formed. It, therefore, appears that the process of conceptual change from a Transmutation model to a Chemical Reaction model will be aided by:

* providing experience of a wide range of substances which pupils observe burning, to include more non-carbon/hydrogen bases substances.
* identifying the products of combustion
* emphasising the role of gases of combustion
* emphasising quantitative aspects of combustion, both weight changes and volume changes.

The Chemical Reaction explanation is capable of being developed to include these aspects, whereas for the Transmutation explanation this is more difficult. Whether such conceptual change is within the cognitive capabilities of the pupils is not clear in the light of Monk´s work, and further research is needed to explore this.

It appears from the current research that many pupils were changing from the Transmutation model to the Chemical Reaction model by adapting the Transmutation model to include aspects of the Chemical Reaction model and the extent to which they did this varied according to the question. White and Gunstone (1992) describe the development of concepts as a continuous multi-dimensional process, that in theory never ends. In changing from one model of chemical transformation to another, pupils develop the precision with which they use the language, replace aspects of the old model with aspects of the new, incorporate new concepts, and sometimes retain aspects of both models simultaneously. In view of the complexity of the change between the models, the process of change will take place over a substantial period of time. Inconsistency in the pupils´ explanations may, therefore, be an indicator of conceptual change.

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APPENDIX: COMPRESSED VERSION OF SELECTED QUESTIONS FROM THE QUESTIONNAIRE.

1.- a) Please explain, in your own words, what you understand by the word 'burning'.

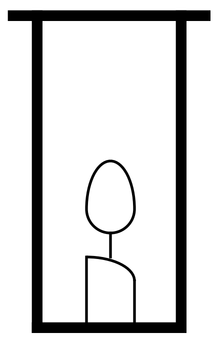
b) What happens to a substance when it burns?

5.- Is anything produced when wood burns?

Yes No Don't know

Please explain your answer.

6.



The candle in the gas jar goes out after a few seconds.

(a) What do you think has happened to the wax of the candle?

(b) What has happened to the air in the gas jar?

(c) Is anything formed that you cannot see?

Please explain your answer.

7.- When a match burns, you see a flame. What is the flame made of?

9.- A student heated 6g of magnesium ribbon in a crucible and it burnt to form a white powder. At the end of the experiment the student weighed the burnt magnesium and found that it now weighed 10g. Why did the weight increase?

a) The oxygen of the air mixed with the magnesium, and because of this the weight increased.

b) When the magnesium was heated, it expanded and so its weight increased.

c) The magnesium reacted with the oxygen of the air, and because of this the weight increased.

d) The magnesium gained heat from the flame, and because of this the weight increased.

e) The result is impossible. The weight cannot have increased.

Please explain your choice: