Models of micro-organisms: children's knowledge and understanding of micro-organisms from 7 to 14 years-old.

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Introduction and background

Micro-organisms are vital to life on Earth. Their increasing use in medicine, food production, environmental protection and other aspects of biotechnology makes it imperative that children should be well informed about these aspects of science (Author, 2006; Gillen& Williams, 1993; Jones & Rua, 2006; Lock 1996; Schaechter, Kolter & Buckley, 2004; Simonneaux, 2002). In contrast to their benign role, the non-beneficial effects of micro-organisms are frequently highlighted in the news and media (Jones & Rua, 2006), frequently under emotive headlines that sensationalize their activities and provide an unbalanced view, for example, 'Killer Germs', The Guardian (2001) and 'Killer Jet Bug', The Mirror (2003). It is therefore increasingly necessary for children to have an informed view, especially as technologies involving micro-organisms develop, so that they are aware of these applications of science and the ethical and social issues they raise (Hill, Stanisstreet & Boyes, 2000; Lock, 1996; Schaechter *et al.*, 2004; Simonneaux, 2002). Including the study of microbiology in appropriate curricula for the 21st Century will help children to understand and appreciate the importance of micro-organisms in their everyday lives so that they are enabled to make informed decisions now and in the future (Harms, 2002; Millar & Osborne, 1998; Osborne *et al.*, 2003; Simonneaux, 2002). Researching the ideas children currently hold about micro-organisms will help to inform and support appropriate curriculum development to achieve these aims. This study considers children's ideas about bacteria, viruses and fungi and uses the term micro-organism to refer to all three microbial groups. For the purpose of this study 'micro-organism' means those living organisms that are microscopic many of which are unicellular.

Research into children's knowledge and understanding of scientific phenomena is now very well established (Driver *et al.,* 1994; Osborne & Freyberg, 1985) and work has been conducted about how children conceptualise different biological phenomena; for example,

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growth (Russell & Watt, 1990); life processes (Osborne, Wadsworth & Black, 1992) and ecology (Leach *et al.*, 1992, 1996) but children's ideas about micro-organisms are under-represented, in comparison to the wealth of information available about some other areas of science, in the research literature (Author, 2006; Jones& Rua, 2006). Even so, some valuable work in this area has been published for example, Au & Romo (1996, 1999); Bazile (1994); Author (2002); Author (2009); Inagaki & Hatano (1993; 2002); Jones & Rua (2006); Kalish (1996a; 1996b; 1997); Maxted (1984); Nagy (1953); Prout (1985); Simonneaux (2000) and Vasquez (1985). These studies indicate that children's ideas about micro-organisms are often incomplete, for example with regard to technological applications of micro-organisms (Bazile, 1994; Author, 2006; Simonneaux, 2000), or their role in maintaining environmental balance (Leach *et al.*, 1996). In addition children and students in all age groups were found to hold alternative ideas for example with regard to their size and morphology. Micro-organisms were often thought of as mini-versions of animals such as beetles, or worms and at times animal-like characteristics, that are anthropomorphized, are bestowed on them, for example heads with facial features or limbs with hands (Author, 2009; Jones & Rua, 2006; Maxted, 1984; Nagy, 1953; Simonneaux 2000; Vasquez, 1985). Micro-organisms are regarded as unpleasant or dangerous and this is frequently related to places where they can be found, such as rubbish bins (Jones & Rua, 2006; Maxted, 1984; Simonneaux, 2000). Their activities were often viewed from an anthropocentric perspective, especially in being a danger or causing illness to humans (Author, 2009; Vasquez, 1985) but the mechanism of infection and subsequent recovery is poorly understood (Au& Romo, 1996; Inagaki & Hatano, 1993; Jones & Rua, 2006; Kalish 1996a; Prout, 1985).

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However, there is little recent work in this field; for example, Nagy's work on the representation of 'germs' by British children aged between eight and eleven years old and

American children between five and seven years old was conducted over fifty years ago. Other studies have concentrated on older students and pupils in different countries; 12-13 year-olds in England (Maxted, 1984) 12-15 year-olds in France (Vasquez, 1985), 15 year-olds in England (Prout, 1985), 18-25 year-olds in France (Rene and Guilbert,1994), French workers in the agro-food industry (Bazile, 1994) 15-16 year-olds in France (Simonneaux, 2000) and grade 5, 8 and 11 students in America (Rua & Jones, 2006). In addition, the methods vary for example, Simonneaux and Maxted interviewed pupils, Nagy asked pupils to draw items and Rua & Jones did both. The aims, number of respondents and the terminology used in each study are varied, making it difficult to compare the findings from each study. This study aims to provide a more comprehensive overview of children's current ideas about micro-organisms across the 7-14 year-old age range using a range of data collection tools in order to deepen our knowledge of this area of science education.

This research is based within a constructivist framework in which the ideas children hold about a concept, phenomenon or event do not necessarily conform to accepted scientific warrants or claims, and these ideas are often derived from everyday experiences rather than from formal learning opportunities (e.g. Driver, 1989; Gilbert, Osborne & Fensham., 1982; Osborne & Freyberg, 1985; Shepardson, 2002). New ideas are either assimilated into existing schema or may be accommodated by creating new schema. This may cause cognitive dissonance if the new ideas, for example, scientifically accurate ideas are not consistent with the learner's existing schema and there may be resistance to accept them. When the new ideas are accepted and connections are made between them and existing ideas learning occurs by enlarging and sophisticating the learner's mental model, although this may take considerable time (Driver, 1989) and may be age dependent (Piaget, 1929).

Gilbert & Boulter (1998:92) define models as representations of 'ideas, objects, events, systems or processes'. Mental models are an individual's images, personal ideas, or internal representations about a particular phenomenon, set of ideas, or concepts (Gilbert & Boulter, 1998). As such, they provide an indication of the ideas held by individuals at a particular point in time (Duit &Glyn, 1996; Greca & Moreira, 2000) although they are not thought of as static entities. Johnson-Laird (1983) considers that mental models are dynamic representations; that they are never complete and continue to enlarge and improve as new information is added. As Ausubel (1968) states, meaningful learning requires the structuring (and restructuring) of specific concepts that relate to existing concepts in the learner's cognitive structure, suggesting a dynamic to-ing and fro-ing of ideas. A mental model can, therefore, provide an indication of what an individual understands about a concept at a particular point in time and includes their knowledge of, as well as his or her beliefs about, the concept. Therefore the study of mental models has increased in science education as a way of helping to understand the process of learning and, in particular, the representational nature of knowledge (Greca & Moreira, 2000). Attempting to define the mental models children hold, at different ages, about micro-organisms, will begin to identify the nature of children's understanding, as well as helping to develop a view of the progression of ideas across the three age groups presented here. Eliciting their expressed models will provide the means to do so.

An expressed model about a concept, phenomenon or event is an external representation of a mental model and can be accessed through a variety of methods including drawing, writing or talking (Buckley & Boulter, 2000). Analsying an expressed model can provide an insight into an individual's conceptualisation of an event, phenomenon, or concept and thus elicit information about the knowledge and understanding an individual has of the concept under

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scrutiny. The relationship between an expressed model, a mental model and the individual’s perceptions of the phenomenon being explored is iterative. An expressed model provides insights into a person’s mental model but as experience through direct or indirect learning occurs, perceptions of that phenomenon will alter, thereby changing the mental model and thus altering the expressed model. Therefore it is relevant to compare the three age groups as a way of exploring how models of micro-organisms change with time and experience. The expressed models of micro-organisms that children of 7, 11 and 14 years hold is explored in terms of:

- classification
- morphology
- size and scale
- living and non-living
- disease and health
- ecology (location and decay)
- technological applications

The expressed models obtained from the data were scrutinised in an attempt to develop a set of mental models that offer some coherence to the range and variety of individual ideas elicited in order to inform pedagogy and curriculum developers.

The research question is:

1. What mental models do children at 7, 11 and 14 years hold about micro-organisms?

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A total of 458 children, 176 aged 7 years, 174 aged 11 years and 108 aged 14 years were involved in the research, although a small number of children in each age group did not complete all tasks due to absence on the day of some of the data collection. All children attend Local Authority (LA) maintained schools in the South of England and the schools have catchment areas that enabled the sample to be broadly representative of the whole population. They included two infant schools, two junior schools, one primary school and one secondary school. The research took place towards the end of the summer term when the children were all at the end of a specific stage in their formal schooling and had been taught the relevant science curriculum (Department for Education and Employment [DfEE], 1999). In England, it has been a statutory requirement since the introduction of The National Curriculum that children between 7+ and 14 years-old are taught about micro-organisms. There is no requirement for children younger than 7 years and therefore these children in this study are unlikely to have any formal education about micro-organisms. The 11 year-olds have been taught that micro-organisms are living organisms, often too small to be seen, and that they may be beneficial, for example in breaking down waste or assisting in the production of bread, or harmful, for example in causing disease or making food go mouldy. The curriculum for 14 year-olds builds on this knowledge to some extent although it deals specifically with micro-organisms in relation to human health. This age group will have been taught how the growth and reproduction of bacteria and the replication of viruses can affect health, and how the body's natural defences may be enhanced by immunisation and medicines. As far as the authors know there was no were no recent media stories or campaigns about micro-organisms that were likely to have influenced children's ideas at the time of the field work.

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The study

A variety of methods and data collection techniques were used to elicit children's ideas enabling them to be probed in depth and from different perspectives; allowing not only an overview of knowledge and understanding, but capturing any qualitative and quantitative changes that occur at each age group. In this way it was anticipated that the data obtained would allow children's expressed models of micro-organisms at the three different ages to emerge providing an indication of progression in conceptual understanding, as well as the development of generalised mental models. The following methods of data collection were employed

- **Drawings**

Reiss *et al.* (2002) suggest that drawings can represent a child's expressed model of a particular phenomenon which is placed in the public domain. Whilst these models relate to, but do not equate with, their mental models (the private and personal cognitive representations), they can provide a useful guide to children's ideas by gathering a rich mass of data with relative ease, as well as supplement other research methods(Hayes, Symington & Martin, 1994; Reiss *et al.*, 2002). The children were asked to draw a picture of a micro-organism and then write down anything about their drawing that they wanted to (Williams, Wetton & Moon., 1989). This instruction may have resulted in children drawing a single item and therefore skewing the data, however this did not universally occur. Drawings and annotations were expected to elicit data across all conceptual areas but analysis revealed that this was not the case. Qualitative analysis was undertaken by attributing characteristics of the drawings and annotations to particular categories and then coding within the categories that emerged from examining and re-examining the drawings (Table 1). Quantitative tallying of the different categories was undertaken to provide frequency and percentage data for each category.

INSERT TABLE 1 ABOUT HERE

- **Brainstorming**

After children had completed their drawings they were asked to turn their paper over and write anything that they knew about micro-organisms (children who had difficulty in writing were provided with a scribe). This technique provided children with the opportunity to undertake a free thinking exercise and allowed them to present their ideas in a different format and was expected to elicit ideas across all conceptual areas. The brainstorms were analysed in the same manner as the drawings, by examining and re-examining the data (Table 1).

- **Concept mapping**

Concept maps are a visual representation of the relationship between different concepts. Kinchin (2000) considers that concept maps are a useful way of collecting information, and because they are flexible, they can be adapted for use by almost any group of learners. The challenge within the context of this research was to design a tool that would be accessible to children in each age group. A new research tool, concept mapping using a photograph association technique (CoMPAT) was developed to overcome these issues (Author). The children were asked to complete concept maps using labeled photographs that illustrate a range of microbial activities which the oldest children in the sample should have some knowledge of as a result of school teaching. The key areas of microbial activity and the photographs that represent the concepts are:

- disease and health (sick child)
- decay (mouldy bread, sour milk, compost heap)

- application of micro-organisms in traditional food technology (bread, beer, yogurt); medication (vaccination and antibiotics) and environmental applications (compost heap and sewage works).

The photograph association concept maps produced by the children were analysed qualitatively and quantitatively. The propositions that children used with each photograph were assigned to a particular category. A scoring system, employing a five point scale (Table 2) similar to that used by Yin *et al.* (2005), was developed to provide an accuracy score for each photograph and therefore a level of the knowledge and understanding held by each year group.

INSERT TABLE 2 ABOUT HERE

For the purposes of categorising the data responses designated scores 2 and 3 were amalgamated. Examples for each level of accuracy can be found in the findings and these were used to guide the responses from other data sets for those concepts.

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- **Semi -structured Interviews**

A sample of children from each age group was selected for a one-to-one semi-structured interview with the intention of enriching the data set further (Abdullah & Scaife, 1997; Denscombe, 1998) and to triangulate information, using a different approach (Cohen, Manion & Morrisson, 2007; Flick, 1998). Approximately ten percent from each age group were selected to be interviewed and these were chosen to provide a representative sample of the cohort, whilst at the same time representing the variety of ideas presented in the drawings and concept maps. This was achieved using intensity sampling to identify those individuals in whom the phenomenon of interest is strongly represented; in this case knowledge and understanding of micro-organisms or the lack of it (Mertens, 1998). The drawings and brainstorms that contained the most accurate, or unusual, answers were selected from each group. This was considered to be a way of representing the full range of views from the cohort. However, this method provided an excess of 'cases'. Extreme, or deviant, sampling in which unusual or atypical responses was employed to reduce the cases for each age group. This sampling method is thought to illuminate the normal situation by studying the extraordinary because they can provide examples of the most clear cut examples of the phenomena being studied (Mertens, 1998). Thus, it was hoped that the children selected for interview in this way would have more to discuss and therefore provide richer data than their peers.

The interviews probed children's ideas about, the structure and appearance of micro-organisms, the variety of micro-organisms, where they can be found and what they do. In addition probes were introduced; a mouldy peach, food products (yogurt, soy sauce, cheese and bread) and a photograph of compost heap, a person sneezing, and antibiotics were used to explore ideas about decay, health and disease and the technological applications of micro-organisms. The interviews were transcribed and the transcripts examined for statements that related to the key conceptual themes within this study; additional and supporting qualitative information was therefore made available. In addition, a numerical tally of how the statements related to the key themes was made, thus providing some quantitative information to support other findings.

- **Development of the expressed and mental models**

Johnson and Gott (1996) discuss the difficulty of interpreting children's ideas accurately. They suggest three methodological principles to evaluate research so that there can be confidence in the reliability and validity of the findings. Firstly that the task(s) children are asked to do is 'neutral'; that is they are accessible to both researcher and child and do not constrain thinking or possible responses. The tasks in this study were open-ended and designed to be suitable for all three age groups. Secondly that any interpretation of responses is made on neutral ground; that is the researcher is aware of the myriad of possible responses. All data were examined and re-examined to ensure any final analysis of data represented all responses. Finally the children's ideas should be explored from different perspectives through triangulation. This has been achieved here through the use of multiple elicitation techniques. Using these principles the study has endeavoured to present accurate expressed models that children have about micro-organisms in relation to the concepts explored. The mental models were developed from a subsequent analysis of the data sets by applying the principles of the scoring system categories used in the concept mapping (Table 2) to the qualitative and quantitative data from at least two sources of data for each conceptual area. These scores are based upon the level of accuracy the responses revealed with respect to definition of micro-organisms provided earlier and what children should have been taught in school about micro-organisms by 14 years. The responses assigned to each score were subsequently categorised as different levels of sophistication to create the mental models for each conceptual area i.e. Emergent = score 1, Transitional = score 2/3 and Extended = score 4.

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Findings

The findings are based upon analysis of all elicitation techniques although particular methods facilitated the representation of certain concepts more readily than others, and therefore may form the main source of data (Buckley & Boulter, 2000).

- **Classification**

Some children in all the age groups in this study classify micro-organisms in a variety of ways (Table 3). The animal and abstract categories are resonant with the findings of previous researchers (e.g. Nagy, 1953; Simonneaux, 2000; Vasquez, 1985). In particular, 7 year-olds considered micro-organisms to be animals, whereas 11 and 14 year- olds were less certain about micro-organisms actually being animals, but considered them to be animal-like, '*it looks like a cockroach'* (11 year-old). Although, some of the oldest children did show uncertainty about how to classify micro-organisms, '*Um, I think they're maybe animals…Cause they like, they're alive and they're not humans. They could be aliens, but I don't think so'* (14 year-old).

INSERT TABLE 3 ABOUT HERE

About one third of youngest children tended to categorise micro-organisms as abstract entities. This age group referred to micro-organisms as things like pieces of dirt, *'germs are little bits of mud that get under your finger nail'* (7 year -old). The youngest children in this study seem to have less understanding of micro-organisms as biological organisms compared to the older age groups. As the understanding of biological concepts increases with age (Carey, 1985; Inagaki & Hatano, 2002; Piaget, 1929) awareness of biological species also increases. The idea that micro-organisms are different from other biological groups and that they are often single-celled increased with age and it is possible that direct teaching about micro-organisms may have influenced children's ideas, although a small but significant percentage (19.1%) of younger children drew cell-like micro-organisms, suggesting that some of the youngest children have an appreciation that micro-organisms are quite separate and distinct from plants and animals, even though they have had no formal teaching about this.

INSERT TABLE 4 ABOUT HERE

'Germ', was used universally by 7 year-olds as the sole term for a micro-organism. Older children used a variety of terms. The way in which they were used indicates that the nature of bacteria, viruses and fungi and how they differ from one another is not clearly understood. 'Micro-organism', 'germ' and 'bacteria' were used generically and interchangeably by many children in a similar fashion to those in Maxted's study (1984). However, others used the terms to refer to different micro-oragnisms and showed awareness that 'micro-organism' and 'germ' are generic terms; this understanding increases with age (Table 4) but some 11 and 14 year-olds used the term '*micro-organism*' to denote one super-ordinate organism which can produce other types, resonating with Simonneaux's (2000) findings. Classification of micro-organisms is difficult for children across the whole age range and this is not surprising, as taxonomists have disputed the exact classification for many years (Bisset, 1963; Woese, Kandler & Wheelis, 1990).

- **Morphology**

What children think micro-organisms look like changes with age, although all categories identified in this study were represented by some children in each age group (Table 5) and are similar to those of previous researchers; for example, Nagy (1953) and Vasquez (1985). A more scientific view of micro-organisms develops with age, although more 11 year-olds drew a recognizable bacterial cell than 14 year-olds and this may be due to more recent teaching. Many of the youngest children consider that micro-organisms look like abstract entities or small animals, and particular species such as, worms, caterpillars, or insects were commonly drawn and referred to, and drawings were frequently anthropomorphised (Figure 1). The 11 year-olds who consider that micro-organisms look like animals tended to refer to insects, whilst both worms and insects were represented in the few animal drawings from 14 year-olds (Figure 1). These children appear to know that micro-organisms are small living things and they have related them to animal species with which they are familiar. Although anthropomorphic ideas decreased with age it is worth noting that these ideas are retained by some, even in the oldest age group (18.0 %), indicating that these views are entrenched, at least for a small percentage of children (author).

INSERT TABLE 5 ABOUT HERE

Cell-like shapes were more commonly drawn by 11 and 14 year-olds suggesting that older children do have some idea that many micro-organisms are unicellular rather than a complex multi-cellular organism and single cells including recognisable bacterial cells were present in some 11 (24.7%) and 14 (16.9%) year-olds drawings (Figure 1 and Table 5). The higher percentage of 11 year-olds drawing recognizable bacterial cells may be accounted for because of recent teaching about microbial morphology whereas the curriculum for the 14 year-olds focuses on micro-organisms in relation to human health. Bacterial morphology, especially bacilli; compared to other micro-organisms is the most commonly represented , and this may be due to exposure to photographs, or drawings in school texts and reference books, or posters in doctors' surgeries, which tend to focus on bacteria. Many of the drawings of micro-organisms as cells, especially those drawn by 14 year-olds attributed the features of typical eukaryotic cells to their drawing, which suggests the influence of current teaching, and some were drawn as a specialised eukaryotic cell e.g. a sperm cell (Figure 1).

INSERT FIGURE 1 ABOUT HERE

- **Size and scale**

Like the findings of previous studies (Nagy, 1953; Maxted, 1984; Simonneaux, 2000), there is a consensus view that micro-organisms cannot be seen with the naked eye, and all age groups seem to know intuitively that micro-organisms are small and cannot be seen without magnification. Reference to size in drawings and brainstorms broadly increased with age (Table 6) and the term '*microscopic*' was used more frequently by older interviewees. What '*microscopic'* means is not generally understood by any of the age groups and familiar small objects such as a speck of dust, the end of a sharpened pencil or a grain of rice to make a comparison were used by 7 and 11 year-olds whilst 14 year-olds used descriptive terms such as '*tiny'* or '*microscopic'*. Standard measures were used infrequently and inaccurately by some 11 and 14 year-olds. Some attempts to use standard measures, for example, a millionth of a metre, were made by 11 and 14 year-olds. Tretter et al. (2006) found that relative size information rather than exact measures were more readily understood and it would appear that the children in this study are employing these ideas intuitively in an attempt to understand the size of micro-organisms. The findings also accord with (Nagy, 1953; Maxted, 1984; Simonneaux, 2000; Vasquez, 1985) and indicate that, whilst there is a good understanding that micro-organisms are very small and the term *'microscopic'* is used widely, there is little real understanding of what this means with respect to the actual size of micro-organisms.

INSERT TABLE 6 ABOUT HERE

Everyday experiences, for example, having a viral infection or seeing fungal fruiting bodies were used as reference points to compare the relative size of micro-organisms. The notion of virulence and rapid proliferation was equated to size in all age groups. This thinking, like the findings of Rua and Jones (2006) and was particularly evident with respect to viruses for 11 and 14 year-olds, '*I've seen like, virus I had rashes, chicken pox is a virus and I've had that ……….um, viruses are quite big because they can spread'* (11 year-old).

- **Living and non-living**

Children in all age groups considered micro-organisms to be living (Table 7). A combination of factors, including the 'seven processes', was used to justify why micro-organisms are considered to be alive (Osborne *et al.*, 1992), although more 7 year-olds compared to other age groups were uncertain about whether they thought micro-organisms were alive. Progression of understanding about micro-organisms as living things increases with age; more complex ideas about what it means to be alive are more frequent in responses from older children. Cell organelles appear more frequently in drawings of 14 year-olds, but their reasoning reverted to established, more secure knowledge, such as reproduction, respiration or excretion when discussing micro-organisms during interviews, 'U*m, they follow certain*

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criteria for living things….such as reproduction, um, excretion, things like that…….Um, I think they, they respire, I think' (14 year-old).

INSERT TABLE 7 ABOUT HERE

Like other studies (Maxted, 1884; Simonneaux, 2000; Vasquez, 1983) movement was commonly offered, as an indicator, by children in all age groups of micro-organisms being alive. Reproduction was also cited, especially by 7 and 11 year-olds, but some 14 year -olds also cite this as a reason for being alive. Teleological reasoning led to reproduction being regarded as an aggressive activity, in terms of the speed and rate of microbial increase and their subsequent proliferation, and as a consequence the harm micro-organisms cause humans. Being dangerous, or causing diseases to humans, was a sufficient reason for being alive for some children in all age groups indicating anthropocentric thinking, *'cause if they weren't alive they wouldn't be able to move to kill people'* (11year-old).

- **Disease and health**

Table 8 shows that one of the most common ideas that the children in all age groups hold is the connection between micro-organisms and disease, *'germs are things that can get inside you and you get ill and poorly'* (7 year-old); *'micro-organisms can make you sick'* (11 year-old). This finding is similar to previous studies , for example, Nagy (1951), Maxted (1984); Prout (1985) and Springer and Ruckel (1992), who found a pathogenic view of micro-organisms was a dominant idea held by individuals of all ages, which Raichvarg (1995) referred to as 'microbe-mania'. More 7 year-olds seem to consider that all micro-organisms are potentially pathogenic, highly infectious and dangerous, *'if a germ gets inside your body you shall be ill'* (7 year-old) compared to 11 and 14 year-olds who indicated a greater awareness that not all micro-organisms are pathogenic. Nevertheless they are not very aware of other causes of disease; only two 14 year-olds mentioned genetic disease during the interviews. Others indicated confusion between microbial and non-microbial diseases, or attributed non-microbial disease to a microbial cause, for example cancer and arthritis. Very few specific pathogens were named and micro-organisms were seen to be generically responsible for illness, *'lots are harmful and cause illnesses*' (11 year-old); *'infection, they can cause flu cold etc, mouldy bread, a nasty thing that goes into your body and destroys everything'* (14 year-old). The majority of children appear to have an exclusively exogenous notion of disease, in which a healthy individual is attacked by micro-organisms and becomes ill. This has implications for children being able to comprehend the nature of genetic disease and, as Simonneaux (2002) points out, it raises questions about students' ability to understand and appreciate the ethical implications of such techniques as ante-natal screening. These considerations raise many sensitive issues with regard to genetic disease. Biotechnologies, using micro-organisms, that enable testing of those pre-disposed to certain genetic diseases, or other heritable characteristics which may be regarded as undesirable, do indeed pose serious ethical issues.

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Younger children tend to think that being in the presence of micro-organisms is sufficient to cause infection, *'if you go near the sick child you shall be ill'* (7 year-old). Whilst a range of ideas about infection are held by older children, such as coughing, sneezing, touching someone, or eating infected foodstuffs. Contradictory ideas about modes and causes of infection were found in all age groups, '*Um, from like, being, if they get like a virus, then they go out in like the cold air straight away, or the, yeah, like they go in the cold air straight away. They kind of like catch a cold'* (11 year-old)*; 'Someone else probably coughed in front of her and the germs went in her mouth.... I got it on Sunday, I'd been... Oh, I'd been at the beach! And I'd been in the water loads and got a cold cause I got cold'* (14 year-old). A germ theory of disease held in conjunction with a non-germ theory, or a biomedical model abandoned in favour of a folklore model of disease when talking about common illnesses such as colds seems to prevail. It would seem that, as Helman (1978) asserts; the folklore model of infection is very persistent, in particular with regard to the common cold and the term 'cold' reinforces association with the environment. Consequently children employ ontological ideas based on everyday experiences, for example, getting cold or going out with wet hair to explain how they had a cold rather than through infection with a rhinovirus.

- **Ecology (Location)**

Previous studies, e.g. Maxted (1984); Vasquez (1985) indicate that the ubiquity of micro-organisms is generally understood, and children in this study indicated that micro-organisms could be found in a variety of locations (Table 9). However, unlike Nagy (1951), who found that young children had a restricted idea about where micro-organisms could be found, more of the oldest children in this study seem to have a more restricted notion that focuses on human beings, as the principal point of microbial location. Connection with humans seems to increase rather than decrease with age and this may be due to the curriculum that focuses on micro-organisms as agents of (human) disease in early secondary school. The notion of ubiquity seems to be more predominant in 11 year-olds' thinking, *'you might, you could find them anywhere across the world. Could be the cleanest place on the planet and you could still find bacteria there'* (11 year-old). Association with unpleasant and dirty conditions is a frequently held idea and the link between this and the threat micro-organisms pose to human health is well established in all age groups. Dirty places, rubbish, dustbins and soil are all cited by children in every age group as places where micro-organisms can be found. Compost heaps and sewage works were also regarded by many children as dirty and unhygienic and they asserted that micro-organisms would, therefore, be found in these places in large numbers.

INSERT TABLE 9 ABOUT HERE

- **Ecology (Decay)**

All age groups associate micro-organisms with decay to some extent, although 7 and 11-year olds focus on food spoilage rather than other forms of decay making a connection with micro-organisms as a threat to health. Therefore it is not surprising that decay is considered negatively. Compost heaps are also viewed, anthropocentrically by 7 and 11 year-olds as dangerous places due to a potential risk from microbial infection.

Table 10 shows children's ideas about decay. Progression about microbial causes of decay occurs between 7 and 11 years but this does not appear to continue to develop. Leach *et al.* (1996) noted that children aged between 5-16 years did not readily cite micro-organisms as the agents of decay but children in this study readily regard micro-organisms as a cause of decay. However the role of micro-organisms in decay is not generally understood and few children seem to know, even at a basic level, that micro-organisms break down organic matter. Those who did offer explanations suggested that micro-organisms feed on, eat or take over the item, '*if you leave bread for a long time it turns mouldy and germs bite into it*' (7 year-old). Alternative ideas, for example, that items will decay 'naturally' as a result of time also seem to stay at a similar level across the age groups indicating that certain ideas persist despite formal teaching or extended personal experience.

INSERT TABLE 10 ABOUT HERE

Everyday experiences of food decay seem to give rise to ontological reasoning about the fate of decaying matter. All age groups considered decaying items would disappear with, or without, microbial activity, although some items, for example, a peach stone was regarded as too hard to decay and would remain intact. Furthermore, the disappearance of some items was regarded as a beneficial outcome of decay, as it would help to clear the environment of such things as leaves in autumn, '*dead bodies and in Autumn when all the leaves fall cause otherwise there'd be lots of leaves everywhere………Um, because then everything is clear and it, the soil can be used for everything to start again*' (11 year-old). The end products of

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decay in the compost heap were *'soil'* or *'compost'* and some 11 and 14 year-olds understand that the soil would be enriched, or that *'nutrients'* would be present, as a result of decay, but and transformation into inorganic products was not considered.

- **Technological applications**

Previous research shows that the use of micro-organisms by humans to manufacture food (Simonneaux, 2000; Williams and Gillen, 1991), for medical products (Maxted, 1984; Simonneaux, 2000), or for environmental benefit is poorly understood. Findings in this study indicate that food production is more commonly recognised as a technological application of micro-organisms compared to both medical or environmental uses and acknowledgement of their use increases with age (Table 11). However, the metabolic processes involved in production of bread, beer and yogurt were not generally understood, and cheese was the only other food product mentioned that might use micro-organisms in its manufacture. Yogurt was associated with sour milk, or allowing the milk to *'go off'* by some 14 year-olds indicating a lack of awareness of the role of micro-organisms in its production. Yeast seems to be considered as a 'universal' micro-organism used in food production, which is probably due to limited experience of science practical work and the influence of food technology lessons.

Micro-organisms were connected with food as potential contaminants by all age groups, especially 7 year- olds, '*Um, because if germs actually made that food, when you have it, it will make you ill'* (7 year-old). Although 11 and 14 year-olds were increasingly aware of the use of micro-organisms in food manufacture the majority of responses also indicated that they too consider micro-organisms mainly as a source of food spoilage and therefore dangerous.

INSERT TABLE 11 ABOUT HERE

The use of micro-organisms in the production of vaccine and antibiotics is not generally understood by any age group and when this application is recognised it is at a simple level; for example, *'good'* micro-organisms being placed in vaccine or antibiotics as the active agent. These findings are similar to those of Simonneaux (2000). The level of alternative ideas also remains relatively stable across all age groups, indicating that some ideas are resistant to change. The specificity of vaccines or antibiotics was not explored and more complex ideas, such as killed or attenuated micro-organisms, or less virulent species used in vaccines were mentioned by only a small minority of children in all age groups. Vaccines and antibiotics are more generally thought of as medication, which is not surprising as this is how the majority of children will have encountered them.

The role of micro-organisms in benefitting the environment is poorly understood and responses to photographs of a compost heap, sewage works, or during interviews suggest that children are unaware of the environmental applications of microbial activity which accords with the findings of Leach *et al.* (1996). Very few children, in any age group, know about the role of micro-organisms in the purification of sewage. Ideas about sewage works being hazardous to human health because of the presence of micro-organisms are retained by all age groups. The positive role of micro-organisms in the environment as a lynch pin in the cycling of matter and as an essential factor in maintaining the ecological balance is not understood by the majority of children in this study.

- **Summary**

Many ideas children hold about micro-organisms are broadly similar across the three age groups, for example, micro-organisms as the cause of disease. Negative ideas about micro-organisms prevail in all age groups, especially in connection with the threat they pose to human health. These and other anthropocentric ideas are held by all age groups. Even though this aspect of children's thinking seems to reduce with age, anthropocentric ideas are retained by a substantial minority (18%) of 14 year-olds.

The ideas that children have expressed about micro-organisms in this study largely concur with the findings of previous studies. This suggests that children's ideas currently are no different to their earlier counterparts and that context or increased teaching does not have a major effect. However the findings provide a more comprehensive overview of these ideas than previous studies and this may be of use to science educators in different countries or at different points in time.

Children's mental models of micro-organisms

Generalised hierarchical mental models (Table 12) have been derived, from the categorization of the data shown in the findings for each of the seven themes explored in this study as explained earlier. The ideas with regard to each key theme specified vary in sophistication and the resulting mental models were categorised as Emergent (score 1), Transitional (scores 2 and 3) or Extended (score 4).

The spectrum of these different levels of sophistication is represented in the ideas of each age group to a greater or lesser extent (Tables 3-11). These models, therefore, offer a generalised portrayal of the ideas held about micro-organisms for the age groups investigated. However, as noted previously, mental models are considered as the personal ideas of individuals; they are therefore idiosyncratic. In attempting to form a model of what each age group in this study thinks about particular aspects of micro-organisms, it is acknowledged that any model offered is a generalization, that any particular individual may hold a subtly different mental picture from those presented here, and that some ideas cannot be included within the generalised models. Nevertheless, the models presented here are formed on the basis of the empirical data about micro-organisms that children in this study hold. They therefore can be regarded as coherent representations of children's knowledge frameworks concerning micro-organisms. As such the models may offer insights into children's ideas about micro-organisms and therefore they are potentially a useful reference tool for curriculum developers to use when considering curriculum content, as well as for teachers when planning teaching sequences.

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Discussion and conclusions

- **The generalised mental models**

The models for each theme represent different levels of sophistication in conceptual understanding. Progression is defined as a gradual change from one level of thinking to another. In terms of children's ideas and their learning, this may be regarded from a constructivist perspective as increasing, or assimilating, new ideas into a mental model, thereby strengthening and deepening conceptual understanding (Johnson-Laird, 1983; Piaget, 1929). The findings indicate that extended models are more frequently held by 11 and 14 year-olds for several key themes, indicating that progression does occur for some children between 7 and 11 years with regard to these concepts (Tables 3-11). A higher proportion of older children hold these more sophisticated models, which would indicate a conceptual change and therefore progression of ideas but little progression seems to occur after 11 years in several key themes, notably, disease, decay, and technological applications of micro-organisms. This is surprising in terms of children's understanding of biological phenomena that is thought to increase with age (Carey, 1985; Piaget, 1929). Furthermore even though progression seems to be most pronounced between 7 and 11 years, it is worth noting that some of the youngest children hold advanced ideas that are congruent with those of their older counterparts. However, it is noticeable that extended models are rarely held by the majority of children in any age group suggesting that restructuring of ideas (Carey, 1985) is difficult to accomplish as children retain previous ideas to avoid cognitive dissonance (Driver, 1989; Whitelock, 1991). In these circumstances conceptual change is less likely to occur (Driver, 1993). The findings indicate that progression does not occur simply as a result of age, maturity, or educational experience in a linear fashion and that learning is not generally so simplistic (e.g. Carey, 1985; Driver, 1993; Harlen, 2000).

- **Implications for curriculum development**

The generalised mental models highlight particular challenges for curriculum developers and may help to inform curriculum development. Considerations for the curriculum include how to capitalise on informal learning especially at an early age, the need to refocus the curriculum at early secondary school to include aspects of microbiology that have been explored in this study rather than only those dealing with human health and to make a case to develop the curriculum so that episodes of learning about micro-organisms are more frequent and topic-based across the age range.

Some very young children appear to understand complex concepts about micro-organisms. However, there is a clear mismatch between children's ability to comprehend these ideas and curriculum content. The current science curriculum in England for 7 year-olds does not include any specific reference to micro-organisms and yet children at this age do have a level of knowledge and understanding that could be used as the basis for formal learning. Adaptation of the curriculum would enable children to learn about micro-organisms earlier than they do at present. This would mean that, rather than starting 'cold' in upper primary this curriculum would have a platform of formal learning episodes on which to build.

Many 14 year-olds do not have the expected knowledge and understanding about micro-organisms and misconceptions remain. Curriculum planners may need to consider how to provide more opportunities to teach about micro-organisms, for example by including microbial morphology and variation, and technological applications of micro-organisms thus expanding the breadth of study rather than the current focus on micro-organisms in relation to human health for this older age group. This would build more coherently on the requirements for 11 year-olds in upper primary school and provide opportunities to revisit topics to facilitate a restructuring of some children's mental models. These alterations may improve levels of knowledge and understanding about micro-organisms so that progression does not plateau after 11years to enable the majority of children to make further progress. As a consequence they may be in a better position later in their schooling, to understand more conceptually challenging ideas for example, genetic engineering and its social and moral implications (Hill *et al*.,2000; Lock, 1996; Schaechter *et al*., 2004; Simonneaux, 2002). .

. (Furthermore, many of the conceptual themes explored in this study are relevant to other aspects of science and the wider curriculum. Planners might reconsider the place of microbiology within the curriculum across the whole age range so that teaching about micro-organisms is more closely integrated within broader aspects of science and other subject areas, such as health, ecology and biotechnology. Developing schemes of work that incorporate the importance of micro-organisms within ecosystems and the technological applications of micro-organisms would provide children with the opportunity to gain a better understanding of the role and importance of micro-organisms *per se* within these fields of knowledge, and as a result they may also develop a more comprehensive understanding of

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these complex concepts (Author, 2006; Gillen& Williams, 1993; Jones & Rua, 2006; Lock 1996; Schaechter *et al.*, 2004; Simonneaux, 2002).

- **Consequences for teaching and learning**

One of the tenets of a constructivist view of learning is that children do not come to a learning situation with an 'empty head' and that everyday experiences influence children's learning (e.g. Driver, 1989; von Glasersfeld, 1989). The models clearly illustrate that children in all age groups have a wide range of ideas embracing the key concepts explored in this study. Furthermore, the ideas that children hold are not necessarily in line with accepted scientific thinking. It is clear from the models that some children in all age groups hold ideas that depart from the scientifically accepted view of micro-organisms. The fact that some 14 year-olds have emergent mental models about particular aspects of micro-organisms suggests that some knowledge is entrenched and highly stable. These alternative ideas appear difficult to change and are retained despite formal teaching, and they are often used to explain concepts which indicate ontological reasoning on the part of these children. It is also worth noting, that even the extended model that has emerged, falls short in many respects of the scientific view of micro-organisms and what 14 year-olds might be expected to know and understand as a result of learning and teaching. These findings have implications for children's future progress in learning about microbiology, as particular concepts may appear unrelated to their own mental models; the gap between what the children think and what is being taught may be too great so that they are unable to resolve potential confusion. In these circumstances, children may prefer to retain their previously held ideas, making conceptual change less likely because of the lack of cognitive dissonance (Driver, 1993), or dissatisfaction with their own model (Strike & Posner, 1982).

Learning about micro-organisms appears to occur in a range of contexts, which includes home and school. Common life experiences appear to have influenced children's ideas, for example, being taught to wash hands after visiting the lavatory, television advertisements and media portrayals of micro-organisms, or being ill. By capitalizing on these informal learning experiences, and making positive use of them from an early age, worthwhile integration of both formal and informal contexts can be achieved. Children could have the opportunity to consider some of their pre-conceptions by discussing their experiences, such as being ill, visiting the doctor or dentist, or discovering mouldy bread or rotting leaves and exploring the role of micro-organisms in these events.

Strong emotional connotations about micro-organisms are evident in the data and the influences of the experiences just described are likely to have made a contribution to children's views, suggesting that children's ideas are to some extent socially mediated. Developing social interaction, as an aspect of pedagogy, by offering opportunities to discuss and reflect on currently held ideas about micro-organisms would allow children to challenge their peers and themselves through the medium of discourse. For example; 11 year-olds could be provided with cartoon images and electron micrographs of micro-organisms and be asked to discuss how best to portray micro-organisms to the general public. Similarly 14 year-olds could discuss newspaper articles that portray micro-organisms as dangerous or harmful and compare them with a scientific account. These activities may help to eradicate the negative perceptions of micro-organisms held in all age groups by encouraging a positive conception of micro-organisms.

Findings also suggest that children divorce science taught in school from everyday ideas, for example, ideas about what causes the common cold. Compartmentalising learning within specific contexts enables different ideas to be held contemporaneously and avoids dissonance (Driver, 1989; Whitelock, 1991). In these circumstances conceptual change is less likely to occur (Driver, 1993). As Novak (2002) indicates, meaningful learning will only take place when there is reciprocal transfer between ideas derived from different contexts, which enables children to make use of ideas derived from the science learnt in the classroom to solve everyday problems. Everyday experiences such as not being able to see micro-organisms, or the severity of different illnesses, suggest that ontological reasoning gives rise to children's ideas about the size and scale of micro-organisms. The notion that micro-organisms are 'microscopic' is generally recognised by children in all age groups. However, the scale and relative size of different micro-organisms is poorly understood. Integrating learning with other aspects of the curriculum; for example, mathematics and geography from the earliest age could provide children with a better understanding of what microscopic really means.

Deleted: Providing ways of developing ideas through argumentation in science is thought to be effective in challenging children's conceptual understanding (e.g. Newton, Driver & Osborne, 1999; Osborne, Eduran & Simon, 2004; Simon, Eduran & Osborne, 2006). Children could be encouraged to debate issues such as the cause of the common cold or microbial virulence. Using argumentation more frequently, as a pedagogical tool, could enable children to develop a more profound understanding of micro-biology. ¶

A greater emphasis on practical work that introduces and sustains work about micro-organisms, from 7 to 14 years may also help to maintain progress (Lock, 1996). For example; making bread and yogurt at 7 years old would provide an introduction to the uses of micro-organisms. Children at 11 years could build on these experiences and explore the fermentation process more thoroughly, including the need for sterile conditions; for example, when making yogurt or ginger beer. Children might then understand the uses of beneficial micro-organisms and those that are not beneficial under certain conditions. The role of micro-organisms as decomposers could be investigated by exploring what occurs in a compost heap. Children at 14 years would be in a position to undertake further practical work that explored the conditions required for these microbial activities. This would enable them to begin to develop their understanding of the metabolic processes of the micro-organisms involved.

In conclusion, children learn about micro-organisms in a range of contexts and from a variety of experiences. Further work is needed in order to discern how, and to what extent these different contexts affect their ideas. However the generalised mental models presented may provide a useful reference point of children's ideas across the 7 to 14 year-old age range to inform pedagogy so that this important aspect of the science curriculum is effectively taught and adequately learned.

References

Abdullah, A. & Scaife, J. (1997). Using interviews to assess children's understanding of science concepts. *School Science Review*, 78, 79-84.

Au, T.K. & Romo, L.F. (1996). Building a coherent conception of HIV transmission: new approach to AIDS education. In D.Medin (Ed.), The Psychology of Learning and Motivation (pp. 193-241). New York: Academic Press.

Au, T.K. & Romo, L.F. (1999). Mechanical causality in children's folkbiology, In D. Medin and S.Atran, (Eds.) *Folkbiology*. Cambridge, MA, MIT Press, 355-401.

Ausubel, D.P. (1968). *Educational Psychology: a cognitive view*. New York, Holt, Rinehart and Winston.

Bazile, J. (1994). Conceptions des operateurs de bas niveau de qualification du secteur agroalimentaire en matiere de microorganimses. *Didaskalia*, 4, 23-37.

Bissett, K.A. (1963). *Bacteria*. Edinburgh & London, E&S Livingstone Ltd.

Brumby, M.N. (1982). Students' perceptions of the concept of life. *Science Education*, 66, 613-622.

Buckley, B.C. & Boulter, C.J. (2000). Investigating the role of representations and expressed models in building mental models, In J.K. Gilbert & C. J. Boulter, (Eds.) Developing models in science education (pp.119-136). Dordrecht, Kluwer Academic Publisher.

Author (2006).

Author (2009).

Author (2010)

Carey, S. (1985). *Conceptual Development in Childhood.* Cambridge, MIT Press.

Cohen, L. Manion, L. & Morrisson, K. (2007). *Research Methods in Education.* (6th edition) London, Routledge.

Department for Education and Employment (1999). *The National Curriculum for England: the programmes of study for science Key Stages 1-4.* London, HMSO.

Denscombe, M. (1998). *The Good Research Guide for Small-scale Social Research Projects.* Buckingham, Open University Press.

Driver, R. (1989). Students' conceptions and the learning of science. *International Journal of Science Education,* 11, 481-490.

Driver, R. (1993). *The Pupil as Scientist?* Milton Keynes, Open University Press.

Driver, R., Squires, A., Rushworth, P. & Wood-Robinson, V. (1994). *Making Sense of SecondaryScience: research into children's ideas.* London, Routledge.

Duit, R. & Glynn, S. (1996). Mental modeling, In G. Welford, J. Osborne and P. Scott (Eds.) *Research in Science Education in Europe*. (pp 166 -176). London, Falmer Press.

Fisher, L. (2003) Killer Jet Bug *The Mirror* 17th March

Flick, U. (1998). *An Introduction to Qualitative Research: theory, method and applications*. London,Sage.

Gilbert, J.K. & Boulter, C. (1998). Models and explanations, part 1: horses for courses? *International Journal of Science Education,* 20, 1, 83-97.

Gilbert, J.K., Osborne, R.J. & Fensham, P.J. (1982). Children's science and its consequences for teaching. *Science Education,* 66, 4, 623-633.

Gillen, A.L. and Williams, R.P. (1993). Dinner date with a microbe. *The American Biology Teacher,* 55, 5, 268-274.

Greca, I.M. & Moreira, M.A. (2000). Mental models, conceptual models, and modelling. *International Journal of Science Education,* 22, 1, 1-11.

Harlen, W. (2000). *The Teaching of Science in Primary Schools.* 3rd edition. London: Fulton.

Harms, U. (2002). Biotechnology education in schools. *Electronic Journal of Biotechnology, 5, 3* (consulted, 15 Dec 2002).

Hayes, D., Symington, D. & Martin, M. (1994). Drawing during science activity in the primary school. *International Journal of Science Education,* 16, 3, 265-277.

Hill, R., Stanisstreet, M. & Boyes, E. (2000). What ideas do students associate with 'biotechnology' and 'genetic engineering'? *School Science Review,* 81, 297, 77-83.

Helman, C.G. (1978). Feed a cold, starve a fever. *Culture, Medicine and Psychiatry,* 2, 107-37.

Inagaki, K. & Hatano, G. (1993). Young children's understanding of the mind-body distinction. *Child Development*, 66, 1,534-1,549.

Inagaki, K. & Hatano, G. (2002). *Young Children's Naïve Thinking about the Biological World.* New York, Psychology Press.

Johnson-Laird, P. (1983). *Mental Models.* Cambridge, Harvard University Press.

Johnson, P. & Gott,R. (1996). Constructivism and evidence from children's ideas. *Science Education,* 80, 5, 561-577.

Jones, M. G. & Rua. M. J. (2006). Conceptions of Germs: Expert to Novice Understandings of Microorganisms. Electronic Journal of Science Education, 10, 3.

Kalish, C.W. (1996a). Causes and symptoms in preschoolers' conception of illness. *Child Development*, 67, 1647-1670.

Kalish, C.W. (1996b). Preschoolers' understanding of germs as invisible mechanisms. *Cognitive Development,* 11, 83-106.

Kalish, C.W. (1997). Preschoolers' understanding of mental and bodily reactions to contamination: What you don't know can hurt you, but not sadden you. *Developmental Psychology*, 33, 79-91.

Kinchin, I.M. (2000). Concept mapping in biology. *Journal of Biological Education,* 34, 2, 61-68.

Leach, J., Driver, R., Scott, P., & Wood-Robinson, C. (1992). Progression in conceptual understanding of ecological concepts by pupils age 5-16. *Leeds: Centre for Studies in Science and Mathematics Education, University of Leeds.*

Leach, J., Driver, R., Scott, P. & Wood-Robinson, C. (1996). Children's ideas about ecology 2: ideas found in children aged 5-16 about the cycling of matter. *International Journal of Science Education*, 18, 1, 19-34.

Lock, R. (1996). Educating the 'New Pasteur'. *School Science Review,* 78, 63-72.

Maxted, M.A. (1984). *Pupils' prior beliefs about bacteria and science processes: their interplay in school science laboratory work.* Unpublished MA thesis, University of British Columbia.

Meek, J. (2001) Killer Germs. *The Guardian,* 24th September.

Mertens, D.M. (1998). *Research Methods in Education and Psychology: integrating diversity with quantitative and qualitative approaches.* California, Sage.

Millar, R. & Osborne, J. (1998). *Beyond 2000: science education for the future.* London: King's College.

Nagy, M.H. (1953). The representation of germs by children. *Journal of Genetic Psychology,* 83, 227-240.

Novak, J.D. (2002). Meaningful learning: the essential factor for conceptual change in limited or inappropriate propositional hierarchies leading to empowerment of learners. *Science Education,* 86, 4, 548-571

Deleted: Newton, P., Driver, R., & Osborne, J. (1999). The place of argumentation in the pedagogy of school science. *International Journal of Science Education*, 21, 5, 553-576.¶

Osborne, J., Wadsworth, P. & Black, P. (1992). *Processes of Life: Primary Space Project.* Liverpool, Liverpool University Press.

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What 'ideas-about-science' should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching,* 40, 7, 692-720.

Osborne, R. & Freyberg, P. (eds.) (1985). *Learning Science: the implication of children's science.* Auckland, Heinemann, 5-14.

Deleted: Osborne, J., Erduran, S., & Simon, S. (2004). Enhancing the quality of argument in school science. *Journal of Research in Science Teaching,* 41, 10, 994-1020.¶

Piaget, J. (1929). *The Child's Conception of the World.* New York. Harcourt Press.

Prout, A. (1985). Science, health and everyday knowledge. *European Journal of Science Education* 7, 4, 399-406.

Raichvarg, D. (1995). *Louis Pasteur – L'empire des Microbes*. Decouvertes Gallimard.

Reiss, M. J., Tunnicliffe, S. D., Andersen, A.M., Bartoszeck, A., Carvalho,G., Chen, S., Jarman, R., Jonsson, S., Manokore, V., Marchenko, N., Mulemwa, J., Novikova, T., Otuka, J., Teppa, S., & VanRooy, W. (2002). An international study of young people's drawings of what is inside themselves. *Journal of Biological Education,* 36, 2, 58-64.

Rene, E. and Guilbert, L. (1994). Les representations du concept de microbe: un construit social contournable? *Didaskalia*, 3, 43-60.

Russell, T. & Watt, D. (1990). *Primary Space Project Research Report: Growth.* Liverpool, Liverpool University Press.

Schaechter, M., Kolter, R., & Buckley, M. (2004). *Microbiology in the 21st Century: Where are we and where are we going?* A report for the American Academy of Microbiology, American Society for Microbiology.

Shepardson, D.P. (2002). Bugs, butterflies, and spiders: children's understanding about insects. *International Journal of Science Education,* 24, 6, 627-643.

Simonneaux, L. (2000). A study of pupils' conceptions and reasoning in connection with 'microbes',as a contribution to research in biotechnology education. *International Journal of Science Education*, 6, 619-644.

Deleted: Simon, S., Erduran, S., & Osborne, J (2006). Learning to teach argumentation: research and development in the science classroom. *International Journal of Science Education,* 28, 23, 235-260.¶

Simonneaux, L. (2002). Analysis of classroom debating strategies in the field of biotechnology. *Journal of Biological Education,* 37, 1, 9-12.

Springer, K. and Ruckel, J. (1992). Early beliefs about the cause of illness: Evidence against immanent justice. *Cognitive Development*, 7, 429-443.

Strike, K.A. & Posner, G.J. (1982). Conceptual change and science teaching. *European Journal of Science Education,* 4, 3, 231-240.

Tretter, T.R., Jones, M.G., Andre, T, Negishi, A. & Minogue, J. (2006). Conceptual boundaries and distances: students' and experts' concepts of scale of scientific phenomena. *Journal of Research in Science Teaching*, 43, 3, 282-319.

Vasquez, E. (1985). Les representations des enfants sur les microbes. *Feuilles D'Epistemologie Appliquee et de Didactique des Sciences*, 7, 31-36.

von Glasersfeld, E. (1989). Cognition, construction of knowledge and teaching. *Synthese,* 80, 121-140.

Whitelock, D. (1991). *Children's Learning and Alternative Conceptions in Science.* Milton Keynes, Open University Press.

Williams, T., Wetton, N. & Moon, A. (1989). *A picture of health: What do you do that makes you healthy and keeps you healthy?* London, Health Education Authority.

Woese, C. R., Kandler, O. & Wheelis, M.L. (1990) Toward a natural system of organisms: Proposal for the domains Archea, Bacteria, and Eucarya. *Proceedings of the National Academy of Sciences*, 87, 4576-4579.

Yin, Y., Vanides, J., Ruiz-Primo, M. A., Ayala, C. C. & Shavelson, R. J. (2005). Comparison of two concept-mapping techniques: Implications for scoring, interpretation and use. *Journal of Research in Science Teaching,* 42, 2, 166-184.

Figure 1: Examples of drawings

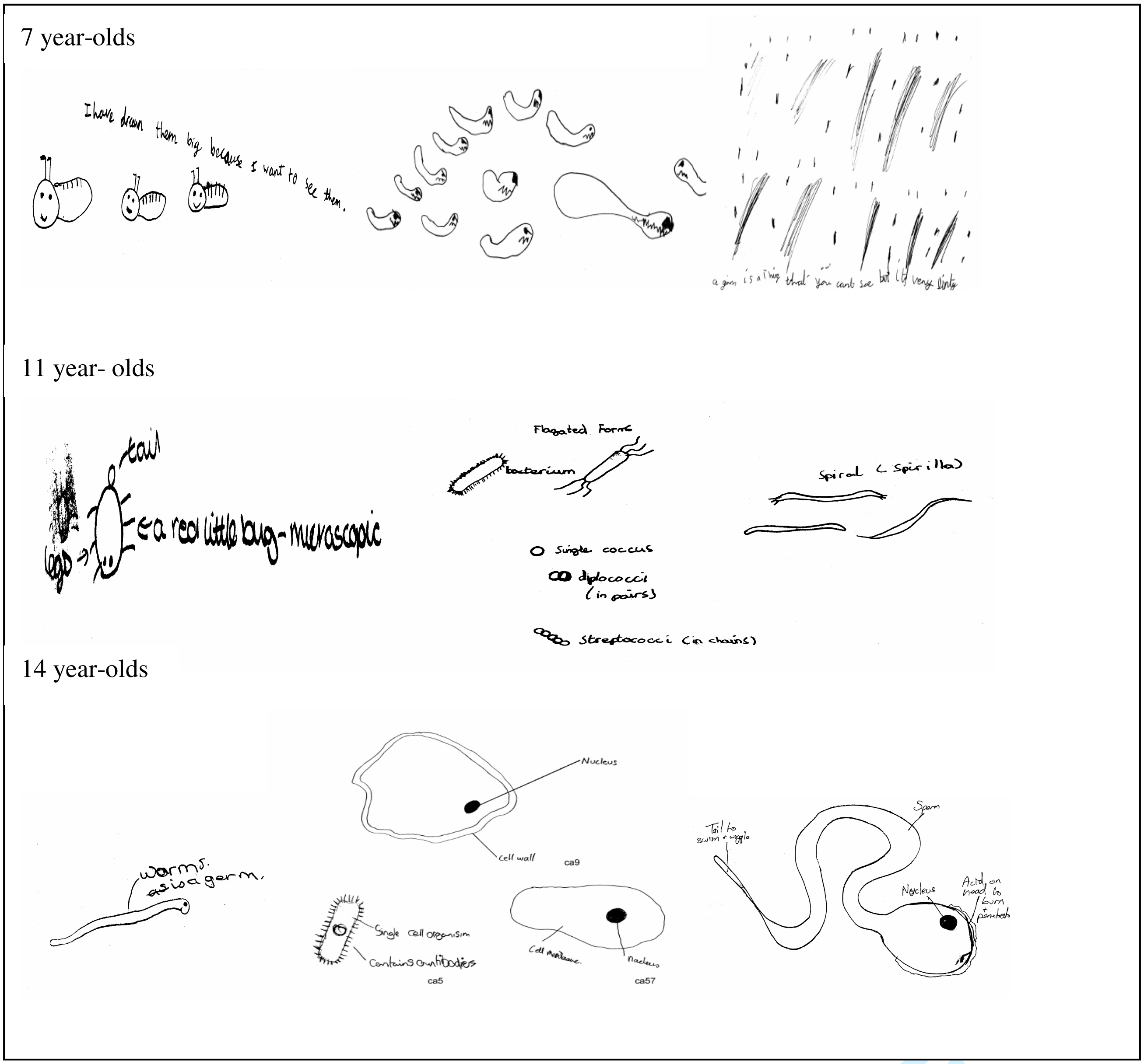

Table 1: Categories for analysis of drawings and brainstorms

Appearance / morphology	Terms	Size and scale	Living	Location	Microbial activity
Amorphous / amoeboid	Micro-organism	Small drawings	Living and/or presence of cell structures	Everywhere	Creates an immune responses
Bacterial cell	Germ	Small	Living processes	In/ on humans	Some are pathogenic
Eukaryotic cell	Bacteria	Microscopic/ requires magnification to be seen	Possibly living / non-living	Dirty/ unhygienic places	All are pathogenic
Animal/ animal like e.g. worms, insects etc	Virus	Actual size		Animals	
Anthropomorphic e.g head, eyes,	Fungus/ mould				
Abstract e.g. dots, squares, lines					
Other e.g. cartoons					

Table 2 : Scoring system for photograph association concept maps

Statement type	Score
Photograph not used / Photograph used without a statement	0
Non-scientific / alternative statement	1
Appropriate statements	2
More detailed / accurate statements	3
Advanced statements /more scientifically detailed	4

Table 3 Classification

Data source	Drawings Total may be more than 100% due to multiple drawings			Interviews			Scoring for mental models
Age group	7 n =159	11 n = 166	14 n = 89	7	11	14	
	Frequency %	Frequency %	Frequency %	n =10	n = 11	n = 9	
Cell like/ single cells	30 19.1	87 52.4	63 70.9	0/10	7/11	5/9	4
Animals/ anthropomorphic e.g., worms, insects	87 54.7	52 31.3	17 19.1	6/10	2/11	4/9	2/3
Abstract e.g. dots, lines,	48 30.2	36 21.7	14 15.7	3/10	0/11	0/9	1
Other e.g. fantasy, cartoons	9 5.7	5 3.0	11 12.4	1/10	2/11	0/9	1

Table 4 Terminology

Data source	Drawings Total may be more than 100% due to multiple terms used			Brainstorms Total may be more than 100% due to multiple terms used			Interviews Total may be more than 100% due to multiple terms used			Scoring for mental models
Age group	7 n =159	11 n = 166	14 n = 89	7 n =139	11 n = 164	14 n = 78	7 n =10	11 n = 11	14 n= 9	
	Freq %	Freq %	Freq %	Freq %	Freq %	Freq %				
Micro-organism/ microbe	0 0	64 38.6	24 30.0	0 0	136 82.9	40 51.3	0/10	11/11	9/9	4
Bacteria	0 0	15 9.0	10 11.2	0 0	48 29.3	35 44.9	10/10	11/11	9/9	2/3
Virus	0 0	3 1.8	5 5.6	0 0	5 3.0	16 20.5	0/10	11/11	9/9	2/3
Fungus/ mould	0 0	0 0	0 0	0 0	4 2.4	1 1.3	0/10	11/11	9/9	2/3
Germ	50 31.4	27 16.1	9 10.1	116 83.5	61 37.2	25 32.1	10/10	11/11	9//9	1

Table 5 Morphology

Data source	Drawings Total may be more than 100% due to multiple drawings			Interviews			Scoring for mental models
Age group	7 n =159	11 n = 166	14 n = 89	7 n =10	11 n = 11	14 n= 9	
	Frequency %	Frequency %	Frequency %				
Single cell/ bacterial cell e.g. bacillus. coccus	10 6.3	41 24.7	15 16.9	0/10	2/11	1/9	4
Amorphous/ recognisable plant/ animal cell	20 12.8	46 27.7	48 54.0	1/10	4/11	7/9	2/3
Animal like e.g. worm, insect	43 27.0	35 21.1	8 9.0	5/10	2/11	1/9	1
Abstract e.g dots, triangles	48 30.2	36 21.7	14 15.7	3/10	1/11	0/9	1
Other e.g. cartoons	9 5.7	5 3.0	11 12.4	1/10	2/11	0/9	1

Table 6 Size and scale

Data source	Drawings			Brainstorms			Interviews			Scoring for mental models
Age group	7 n =159 Frequency %	11 n = 166 Frequency %	14 n = 89 Frequency %	7 n =139 Frequency %	11 n = 164 Frequency %	14 n = 78 Frequency %	7 n =10	11 n =11	14 n= 9	
Microscopic/ requires magnification	14 8.8	22 13.3	5 5.6	11 7.9	39 23.8	35 44.9	10/10	11/11	9/9	4
Small	8 5.0	16 9.6	8 9.0	5 3.6	33 20.1	17 21.8	0	0	0	2/3
Small Drawings	42 26.4	65 39.2	35 39.3	-	-	-	-	-	-	1

Table 7 Living and non-living

Data source	Drawings			Brainstorms			Interviews			Scoring for mental models
Age group	7 n =159	11 n = 166	14 n = 89	7 n =139	11 n = 164	14 n = 78	7 n =10	11 n = 11	14 n= 9	
	Freq %	Freq %	Freq %	Freq %	Freq %	Freq %				
Living / cell structures	33 20.8	64 38.7	67 75.3	0 0.0	1 0.6	18 23.1	0/10	0/11	5/9	4
Life processes	159 100.0	166 100.0	47 52.7	26 18.7	92 56.2	35 44.9	9/10	11/11	4/9	2/3
Possibly living/ non- living	48 30.2	36 21.7	14 15.7	1 0.7	3 1.8	2 2.6	1/10	0/11	0/9	1

Table 8 Disease and health

Data source	Drawings			Brainstorms			Concept maps Responses to photo of sick child			Interviews			Scoring for mental models
Age group	7 n =159	11 n = 166	14 n = 89	7 n =139	11 n = 164	14 n = 78	7 n = 173	11 n = 169	14 n = 103	7 n =10	11 n = 11	14 n= 9	
	Freq %	Freq %	Freq %	Freq %	Freq %	Freq %	Freq %	Freq %	Freq %				
Microbes cause immune response	0 0	0 0	0 0	4 2.9	0 0	0 0	4 2.3	4 2.4	1 0.9	0/10	1/11	1/9	4
Some microbes are pathogenic	0 0	3 1.8	2 2.2	21 15.1	75 45.7	14 18.0	22 12.7	60 35.5	22 21.4	3/10	6/11	7/9	2/3
All microbes are pathogenic	9 5.7	5 3.0	2 2.2	50 40.0	20 12.2	14 18.0	103 59.5	53 31.4	36 35.0	7/10	4/11	1/9	1

Table 9 Location

Data source	Drawings			Brainstorms			Interviews			Scoring for mental models
Age group	7 n =159	11 n = 166	14 n = 89	7 n =139	11 n = 164	14 n = 78	7 n =10	11 n = 11	14 n= 9	
	Freq %	Freq %	Freq %	Freq %	Freq %	Freq %				
Everywhere	0 0	3 1.8	0 0	1 0.6	24 14.6	1 1.3	1/10	2/11	0/9	4
Humans	9 5.7	17 10.8	1 1.1	25 18.0	50 30.5	14 17.9	2/10	4/11	7/9	2/3
Dirty /unhygienic places	7 4.4	7 4.2	1 1.1	17 12.2	6 3.7	2 2.6	5/10	5/11	3/9	1
Animals	6 3.8	0 0	0 0	8 5.9	2 1.2	0 0	2/10	0/11	0/9	1

Table 10 Decay

Data source	Concept maps Photos of compost heap = CH, mouldy bread = MB, sour milk = SM,									Interviews			Scoring for mental models
Age group	7 n = 173			11 n = 169			14 n = 103			7 n=10	11 n = 11	14 n= 9	
	Frequency %			Frequency %			Frequency %						
	CH	MB	SM	CH	MB	SM	CH	MB	SM				
MOs cause decay that can be beneficial and detrimental	0 0.0	0 0.0	0 0.0	2 1.2	7 4.1	2 1.2	2 1.9	0 0.0	0 0.0	0/10	0/11	0/9	4
MOs cause decay	12 6.9	74 42.9	32 18.6	35 20.7	96 56.8	72 42.6	28 27.2	40 38.8	26 25.2	3/10	11/11	8/9	2/3
MOs cause decay and this is harmful	47 27.2	35 20.2	27 15.6	26 15.4	22 13.0	31 18.3	19 18.4	22 21.4	25 24.3	7/10	0/11	1/9	1

Table 11 Technological applications

Data source	Concept maps Food production = photos of bread (Br) , beer (Be) and yogurt (Yo) Medical = photos of vaccine (V) and antibiotics (A) Environmental = photos of compost heap (CH) sewage works (SW)									Interviews			Scoring for mental models
Age group	7 n = 173			11 n = 169			14 n = 103			7 n =10	11 n =11	14 n= 9	
	Frequency %			Frequency %			Frequency %						
Food production	Br	Be	Yo	Br	Be	Yo	Br	Be	Yo				
MOs metabolism exploited	0 0.0	0 0.0	0 0.0	2 1.2	2 1.2	0 0.0	3 2.9	1 0.9	1 0.9	0/10	1/11	0/9	4
MOs used	0 0.0	0 0.0	0 0.0	32 19.0	41 24.3	44 26.1	35 34.0	38 36.9	21 20.4	1/10	7/11	9/9	2/3
MOs too dangerous	3 1.7	28 16.2	7 4.0	24 14.2	33 19.5	35 20.7	11 10.7	11 10.7	27 26.2	9/10	4/11	0/9	1
Medical (antibiotics and vaccine)	V		A	V		A	V		A				
MOs used	0 0.0		0 0.0	2 1.2		0 0.0	5 4.9		0 0.0	0/10	1/11	3/9	4
Good MOs used	2 1.2		1 0.6	26 15.4		32 18.9	15 14.6		8 7.8	1/10	5/11	4/9	2/3
Antibiotics and vaccine kill MOs	37 21.4		31 17.9	76 45.0		76 45.0	50 48.6		64 62.1	2/10	5/11	2/9	1
Environmental	CH		SW	CH		SW	CH		SW				
MOs are decomposers	0 0.0		0 0.0	2 1.2		3 1.8	2 1.9		1 0.9	0/10	0/11	2/9	4
MOs use organic matter to multiply	12 6.9		1 0.6	35 20.7		5 3.0	28 27.2		9 8.7	0/10	3/11	7/9	2/3
MOs are not beneficial	47 27.2		28 27.7	26 15.4		72 42.6	19 18.4		38 37.9	10/10	11/11	9/9	1

Table 12: Generalised mental models of children's ideas about micro-organisms

Key theme	Emergent	Transitional	Extended
Classification			
○ **Grouping**	non- biological entities, variation is based upon the level of virulence and the threat to human health	animal or animal-like, variation within groups is based upon appearance and activity which includes harm done to humans	single celled living organisms and distinct from plants and animals, variation within groups is generally based upon appearance and activity
○ **Terminology**	single term used to one group generally referred to as germs	multiple terms used to refer to different groups which include micro-organisms, bacteria, germs and possibly fungi and viruses	multiple terms used to refer to different groups within the umbrella term 'micro-organism' these include bacteria, fungi, viruses, 'germ' is also a generic term
Morphology			
○ **External appearance and features**	little animals, usually invertebrates and often anthropomorphised or human-like characters or abstract often geometric shape, anthropomorphic external features which may illustrate a harmful appearance	amorphous single 'cell' or recognisable plant or animal cell, may have external features e.g. hairs	single cells, some recognisable as bacterial cells, may have external features e.g. cilia/ flagella
Size and scale	Small, actual size not understood, size sometimes related to virulence	small / microscopic, size explained using everyday objects or specific vocabulary as a reference point	microscopic, requires magnification to be visible, size sometimes referred to in standard measures (but not necessarily understood)
Living and non living	non living / possibly living	living, evidence-based on living processes especially movement and reproduction, as well as anthropocentric ideas, e.g. harm caused to humans	living, presence of cell structures/organelles included as evidence of living
Disease, heath and hygiene ○ **Disease and Infection**	all micro-organisms are potentially pathogenic and highly infectious, especially to humans, levels of virulence are not differentiated, illness is a spontaneous reaction to the presence of micro-organisms, contradictory ideas about modes of infection exist	not all micro-organisms are pathogenic, micro-organisms cause diseases, especially in humans, levels of virulence are not recognised, modes of infection focus on human transmission, contradictory ideas exist about modes of infection	not all diseases are caused by micro-organisms, some micro-organisms are pathogenic, the symptoms of illness are as a result of immune response to microbial activity, focus on human illness, levels of virulence may be recognised, various modes of infection are known although contradictory ideas still exist
Ecology			
○ **location**	micro-organisms are associated with dirty, unhygienic places and animals, and as a result are a hazard to humans, micro-organisms exhibit free will and emotions about their location	micro-organisms can be found everywhere but especially noted for association with humans and are potentially harmful, micro-organisms exhibit free will and emotions about their location	micro-organisms can be found everywhere
○ **decay**	decay is a result of age or physical conditions, decaying items (food, compost, sewage) are dangerous especially to humans and can cause illness because of the presence of micro-organisms, decaying items 'go bad' , change physically and may eventually disappear, all	micro-organisms associated with decay items, cause decay by 'eating' items, decaying matter (food, compost or sewage) can pose a threat to human health because of the presence of micro-organisms, some forms of decay are	decay requires a combination of environmental and physical factors for microbial growth, decaying item will change and eventually disappear, decay can be beneficial as a litter prevention mechanism or to provide nutrients in the soil

	forms of decay are regarded negatively and positive role of micro-organisms in decomposition not recognised	regarded negatively, decaying items change physically and eventually disappear but some items are too hard to decay, the soil is the main end point for decaying items	
Technological applications			
○ **food**	micro-organisms cannot be used to make food because they are dangerous (to humans)	micro-organisms are used to make certain food stuffs, yeast is the universal micro-organism used in the production of food	some microbial metabolic activities enable them to be used in the production of food stuffs
○ **medical**	vaccine and antibiotics are antimicrobial agents and kill pathogenic micro-organisms, cure (human)diseases caused by micro-organisms	micro-organisms are used in the manufacture of vaccine and antibiotics, vaccine and antibiotics contain 'good' micro-organisms to fight or kill 'bad' micro-organisms that cause (human)disease, vaccine can prevent further infections.	micro-organisms are used to produce vaccine and antibiotics, dead, attenuated, less pathogenic micro-organisms are used in vaccine to prevent diseases acquired immunity conferred as a result of vaccination, antibiotics not effective on viral infections
○ **environmental**	micro-organisms are dangerous to humans and are not beneficial to the environment, compost heaps and sewage works are dangerous because of the presence of micro-organisms and pose a threat to human health	micro-organisms can be useful to decompose matter to provide nutrients for the soil, compost and sewage is used by micro-organisms as a medium in which to grow and multiply and compost heaps and sewage works are therefore a potential source of danger to humans due to the large number of micro-organisms present	micro-organisms decompose organic matter and may help the environment as 'cleaners' e.g. in the purification of water and removal of organic 'litter'