20th December 2001

For the

VATICAN PONTIFICAL ACADEMY

OF SCIENCE CONFERENCE

(Casino Pio IV, 19-21 November 2001)

"Science in the Twenty First Century"

Hands-on Science

Professor Richard L, Gregory CBE, DSc, LLD, FRS

Department of Experimental Psychology,
University of Bristol
Bristol BS8 4JX
England. UK

Presenting science and technology, Hands-on to children and the general public, is not a new idea. It was clearly expressed nearly four hundred years ago by Francis Bacon, in his unfinished book **New Atlantis** (1626), which describes how the technology and science of his day could be made available to everyone. Francis Bacon describes his House of Saloman, as having:

Perspective Houses, where we make demonstrations of all lights and radiations; and of all colours; and of things uncoloured and transparent, we can represent unto you all several colours; not in rain-bows, as it were in gems and prisms, but of themselves single. We represent all multiplications of light, which we carry to great distance, and make so sharp as to discern small points and lines; also all colourations of light. . . We procure means for seeing objects afar off, and things afar off as near; making feigned distances. . .

We have also engine houses . . . We imitate also flights of birds; we have some degree of flying in the air; we have ships and boats for going under water, and brooking of seas; also swimming girdles and supporters. We have diverse curious clocks, and other like motions of return, and some perpetual motions. We imitate also motions of living creatures, by images of men, beast, birds, fishes and serpents. . . .

We have also a mathematical house, where are represented all instruments, as well as geometry and astronomy, excuisitely made.

Bacon saw that science could, and should, be a social activity with all kinds of contributions according to individual abilities and personal interests. He emphasized *methods* of enquiry and discovery, and stressed the importance of useful inventions deriving from questioning and research. It could be claimed that he invented planned organized research and the use of science for practical ends. Bacon's **Novum Organum** of 1620 set up rules for scientific method, which inspired the foundation of the Royal Society in 1660; but nothing came of his **New Atlantis** dream - though then as now the future depends on children coming to appreciate how science works, and what it does and fails to do.

The principal modern pioneer of Hands-On science is Frank Oppenheimer (1912-1985), who founded the *Exploratorium* in San Francisco in 1969. Oppenheimer wrote (1976): 'I suspect that everybody - not just you and I - genuinely wants to share and feel at home with the cumulative and increasingly coherent awareness of nature that is the traditional harvest of scientists and artists." He said of his exhibits (Murphy 1985), 'We do not want people to leave with the implied feeling: "Isn't somebody else clever."' Our exhibits are honest and simple so that no one feels he or she must be on guard against being fooled or mislead.' Yet, though he was a physicist, Frank Oppenheimer loved the subjective phenomena of illusions of perception. He saw them as a way to introduce the observer - us - into science's account of the universe.

Three and a half centuries earlier, Bacon included in his *House of Salomon* - in which there were to be Houses of Mathematics, Engines, Instruments for measuring, and all the science and technology of the time – demonstrations of perception and illusion::

> *We have also Houses of Deceits of the Senses; where we represent all manner of juggling, false apparitions, impostures, and illusions; and their fallacies. And surely you will easily believe that we have so many things truly natural which induce imagination, could in a world of particulars deceive the senses, if we could disguise those things and labour to make them seem more miraculous.*

The recent popularity of Exploratory Science Centres, shows that a significant proportion of the public of all ages find direct experience of science entertaining and interesting (Pizzey 1987). For example, generally following the *Exploratorium* in San Francisco, there are the unusually well endowed Toronto Science Centre, and the astoundingly ambitious Parc La Villette in Paris. The first in Britain was the *Exploratory* in Bristol, which after twenty years was to be superceded by Lottery-funded *Explore*; then *Techniquest* in Wales, in Cardiff; and now some forty Centres and Galleries in Britain including Birmingham, Manchester, Sheffield, Liverpool and Glasgow. There are science and technology Centres in almost all European countries and around the world, including: Italy, Australia, India, Singapore, Switzerland, South America and so-far small Centres in Africa; though not yet in Russia,. The physicist Professor Paolo Budinich has been striving for many years to make his "Laboratory of the Imagination" a major Centre open to the public in Trieste, and is gradually succeeding. A large Science Centrte has openrd recently in Naples. This is now a widespread rapidly growing movement, with the coordinating organization ASTC (Association of Science and Technology Centers in America, and the European ECSITE (Consortium of Science Industry and Technology Exhibitions) co-ordinating all European countries.

An important question is: Do interactive, hands-on Science Centres, really convey science? With their necessarily quick and easy demonstrations are they much more than Fun Fairs? Certainly there are similarities. But it is interesting that even when there is similar apparatus (such as almost zero-friction pucks on an air table, for a Fun Fair's game and in Science Centres to demonstrate Newton's First Law of motion) they are handled differently and apparently are seen differently, by children and adults.[1] The context and 'atmosphere' is very important for how things are seen. Possibly though, as suggested by Michael Shortland (1987), we have been too free with phrases such as "Science is Fun", for much of science is tedious, difficult and sometimes dangerous. And science has social and moral implications which it is most unwise to ignore. This charge of triviality is important. It needs to be met with evidence of what people do get from Hands-On learning, but unfortunately hard data on this is not readily available and is difficult to obtain.

But it is hard to believe that learning can't be fun. There are experiments with children showing that games, and active involvement of many kinds, aids learning (Hodgkin 1985). There is strong evidence that babies and children learn to see by hands-on (and mouth-on) experience, especially from the germinal work of Jean Piaget (Piaget 1929, 1952, 1955).

Perhaps most dramatically, the power of Hands-on experience as the basis of visual perception is shown by some rare cases of adults who were blind at birth, or at infancy, then recovered sight by eye operations when adult. Some of these people see, almost immediately, things that they had learned through their early touch experience; but are effectively blind for objects they knew nothing about before the operation (Gregory and Wallace 1963, Valvo 1971). For Gregory

[1] This is rather like a frame affecting how a picture is seen..

and Wallace's patient 'S.B’, upon first being shown an object (in the Science Museum in London) which for years he had wished he could use - a lathe - S.B. was frustrated. For although it was there in front of him, he could not *see* it. It was meaningless, until he shut his eyes and ran his hands over it. Then he stood back, and said: "*Now I've felt it, I can see.*" He then described the lathe he saw for the first time, with considerable accuracy.

The importance of hands-on experience for learning and discovery is of course very clear in the history of science. This is generally accepted for modern science; but it now seems that there was an infra-structure of surprisingly sophisticated technology behind Greek science and philosophy (Sarton 1952, Clagget 1957, Sambursky 1987).[2]

It seems that both the development of science, and individual perception and understanding, require interactive experience with objects (including working models that can be constructed and handled) to approach and appreciate abstract theoretical principles. But unfortunately much generally available hands-on experience is misleading. The genius of Galileo and Newton was to select appropriate experience - in in Galileo's apparatus in the Florence Science Museum - which is a perfect for today's hands-on Science Centres..

The importance of active touch precedes humans. There are many studies on animals showing the importance of active touch exploration for learning to see, such as the ingenious experiment of Richard Held and Alan Hein (1963), on a pair of kittens in baskets which were free to move but linked together. One of

---

[2] This is shown most dramatically with the discovery of an elaborate Greek astronomical computer c. 80 BC, found by pearl fisherman in 1900, in an ancient ship that sank near Greece off the island of Kythera. The American historian of science Derek de Solla Price describes an elaborate geared calendar mechanism designed to represent with remarkable accuracy astronomical cycles, especially of the Sun and Moon. The existence of this mechanism (and there are references to such mechanisms of several hundred years earlier, on public display in Greece) shows an active technology of metallurgy and applied mathematics, with remarkable mechanical skill. This suggests that Ptolemy's system of epicycles for explaining planetary movements was almost certainly built, with working models used as thinking tools for explaining the science of their day. As shown by the remarkable work of Joseph Needham (19xx) much the same is true for China.

the kittens was free to move as he wished; but the other, could only follow passively n his linked basket - so he had similar visual inputs, but lacked voluntary control of where he moved. It was found that the 'active' kitten learned normally; but the linked 'passive' kitten did not learn to see, remaining effectively blind.

It is sometimes claimed that young children do not start with a ‘blank sheet’, but rather from very early on have their own explanations - which are remarkably Aristotelian, and they may be very hard to shift (Driver, Guesne and Tiberghien 1985; Matthews 1980). Presumably children's '*naive theories of science'* (as sometimes called), derive from their everyday hands-on experience from infancy. The conclusion is inescapable, that although hands-on experience is effective - indeed essential, for learning to see and understand - it can hardly be adequate for arriving at *scientific* understanding. More is needed, if only because many basic principles and phenomena are normally masked, by for example 'poluting" friction. The normal world is not a good hands-on Science Centre! So children are quite largely misled by their everyday experience. Designers of toys might do a lot to improve matters.

One might say that Aristotle’s, rather than Galileo’s physics, is suggested by everyday hands-on experience of pushing objects and so on. Specially designed Science Centres can, for example, (almost) remove friction from moving objects, to reveal Galileo’s principles, for children’s individual discovery.

Is it possible that children *need* to live for years with an Aristotelian view of physics? Is there perhaps some kind of innate structuring, and inborn development, that we may upset with risk of harm? Also, where facts are concerned, is it perhaps best to let children learn facts isolated from interpretation - so they can build up their own cognitive structures, in their own ways, appropriate to their generation? There is certainly a danger of teachers imposing out-moded unhelpful ways of seeing and thinking. The alternative, is to promote originality in children, and expect them to develop in their own, largely unpredictable ways.

If we are able to stimulate originality through individual experimenting, how do we know that children will be better off, than when given at least a basis of accepted knowledge and beliefs? Surely we should try to assess effects of Hands-On experience with controlled experiments, comparing effects of interactive experience with other ways of presenting phenomena and ideas to children. But, for such educational research on how understanding may be be gained - how can we *measure understanding?*

Perhaps the greatest danger for a Science Centre open to the public, is switching visitors off by appearing intimidating. For the habits of mind needed for entering the Magic Circle of science, are intimidating for many people - perhaps because Science Centres were not been available them, when they were children! It is well known that mathematical formulations are generally incomprehensible and scary. Indeed, looking for logical structures in ordinary arguments can be seen as rudely challenging; so the problem goes beyond mathematics, and is very general. Research is needed on how to introduce effective rigorous science-thinking into Science Centres.

It is remarkable how little science there is in traditional Science Museums. It is generally impossible to find concepts of force, energy, Relativity, Quantum physics, or computing in museums. There are motor car museums that do not show how an engine works; computer museums which do not show how mechanisms can represent and handle numbers. Conventional museums should gain with Hands-On experience. For without it, visitors are blind to the most significant collections of fossils, engines, or even the apparatus of science presented in glass cases..

Returning to perception itself, Frank Oppenheimer said (1983):

> The Exploratorium introduces people to science by examining how they see, hear and feel. Perception is the basis for what each of us finds out about the world, and how we interpret it - whether we do so with our eyes or develop tools such as microscopes or accelerators.

Paradoxically, perhaps the most effective way to see our own role and limitations as observers and 'understanders' is through the intriguing phenomena of *illusions,* of vision and the other senses. These are wild and wonderful deviations from the physical world: deviations which may seem closer to fantasies of art, than to verities of science; yet they illuminate *us* as observers and so as scientists.

However curious this may be, phenomena of illusions reveal tenuous links of perception, by which we appreciate ourselves and our relation to the world. Apart from their own interest they serve to warn us that we must check our perceptions, and question even what may seem most clearly true. As Frank Oppenheimer found (and I helped him in this at the start of the Exploratorium), these 'subjective' though often explainable phenomena help the visitor to be aware of what it is to observe and understand - through recognising failures to observe and understand.

Then pendulums, locks and keys, clocks, pucks floating on air, elliptical billiard tables - almost *anything* - takes on richer meaning. But to see these as meaningful phenomena of science considerable help may be needed. It takes genius to read phenomena without help by help from the past. Indeed the hisytory of science can be most revealing and helpful.

Even without knowledge of the ways things work, it is wonderful to experience the surprising forces of gyroscopes, magnets, inertia, patterns of spectral lines in glowing gasses - to discover the same patterns in light in stars. To go on, for example to appreciate the Red Shift, and how this tells us the Universe is expanding and that we can see billions of years back in time, it is necessary to understand abstract principles such as the Doppler shift. Additional sources of information are needed. Then Science Centres can be useful resources for schools, and are symbiotic with schools.

Handling Explanations

Following initial *hands-on* experience, there are various kinds of understanding. There are what we might call '*Hand-Waving*' explanations, which though satisfying and useful are not strictly justified or proved. Then, there are mathematical accounts - generally preferred by scientists - that we might call, '*Handle-Turning*', They capture computing and mathematics, with the essentially mechanical processes of algorithms.

So, we have a *handy terminology:*

HANDS-ON	Interactive experience	***Explorations***
HAND-WAVING	Common-sense	***Explanations***
HANDLE-TURNING	Mathematics	***Computations***

Commonly held Hand-Waving assumptions may be hopelessly wrong, and misleading. The assumption here, is that initial hand-waving explanations may be corrected by selected hands-on experience, and refined and quantified by Handle-Turning scientific methods of mathematics.

Hand-waving explanations (in spite of science) remain important. An interesting example is understanding the gyroscope's tendency to turn ('precess') at right angles to tilt, and vice versa. For some scientists, a mathematical account is essential. But with *no mathematics* one can see what is happening, directly from Newton's First Law of motion, (that moving bodies resist imposed changes of direction or velocity. This applies to each 'point mass' of the spinning wheel)[3]

Signs of Understanding

How can we measure effects of Hands-On experience for gaining understanding?

There are well-established ways of assessing knowledge in schools. These include the written questions of formal examinations. They may also be open-ended essays, or multiple-choice questions. The latter are easily run by computer; the former is more revealing but requires skilled assessment, so is expensive. If only to prevent Exploratories looking like schools, which they are not, we should develop different kinds of assessment - which may useful for research into effects of hands-on experience

1) Surprise: A powerful technique is to set up situations for *predicting* - where correct prediction requires and so demonstrates understanding of what is going on. Clearly defined and usually simple situations should be set up. False predictions can be clear evidence of

---

[3] Consider the changes of direction of its point-masses, composing it. When the spinning wheel is tilted, say to incline to the right, the point-masses at the wheel's front and back are forced to change direction - which they resist by Newton's Law - though the point-masses at the top and bottom are shifted sideways but not changed in their direction of motion. So they hardly resist the wheel being tilted. The resistance to change of direction of the vertically moving point-masses produce a force at right angles - horizontal - which turns the wheel right or left, according to its direction of spin. The opposite happens when the wheel is turned right or left - then it 'precesses' at right angles to tilt to one side. Once one 'sees' this one understands the essential principle of gyroscopes, and one can predict which way it will precess for any turn or tilt, with either direction of spin - with no mathematics. And having seen it in this way the mathematics takes on meaning. By experiencing these forces interactively, for building informal hand-waving intuitive conceptual models in one' mind, one is set up to understand the mathematics - which allows precise generalizations even to all situations and is essential for *designing* for example gyro-control systems. I suggest that the major aim of interactive Science Centres, after stimulating interest and curiosity should be setting up Hand-Waving explanations giving useful intuitive accounts. They are vital for meaningful seeing, and for going on to rigorous Handle-turning mathematics which is so important for much - though not all - science and technology. It is interesting that almost all scientists use Hand-Waving mental models, images, and analogies for their creative thinking. The greatest, Newton, was skilled at Hands-On model and toy making; thinking up rich working Hand-Waving accounts of light, gravity and much else before attempting to arrive at his wonderfully broad and powerful Handle Turning mathematical formulations of Laws of nature.

inappropriate mental models of the situation. A classical example is Aristotle's rejection of the notion that the stars appear to move because the earth spins round. He jumped up - and landed in the same place - so how could the Earth have been spinning under him? What Aristotle lacked was the concept of inertia. This shows how important concepts are, and how soon we depart from common sense in science.

2) Analogies: A further test of understanding at a more-or-less deep level is ability to see analogies. If one understands, for example resonance, then similarities and deep identities are seen between what on the surface are different-appearing things or phenomena, such as: musical instruments; the divisions of Saturn's rings; tuned radio circuits; the positions of spectrum lines given by resonances within atoms. It is clearly important to have *many examples* of different-appearing phenomena to practice seeing analogies.

We may look at *increased power* to see analogies for assessing effects of hands-on experience Here again the importance of a rich variety of examples is clear, for this allows not only discovering basic principles common to many examples (which is surely the key to creative intelligence) but also is a means for setting up on-the-surface surprising predictions - which by succeeding or failing *surprisingly* can test understanding. (Sir Karl Popper emphasizes failures of prediction as necessary for gaining knowledge; but surprising positive predictions are, surely, just as effective though perhaps rarer).

3) Inventing: We may look for ability to fill in gaps, and invent novel solutions - where gap-filling or inventing requires more-or-less deep understanding. An example would be filling in or inventing hidden parts of mechanisms. One can only see into black boxes by understanding them.

4) Jokes: With increasing spread of understanding of science and technology we may look for more widely shared humour - which will surely enliven literature and life. Ability to see and to make jokes is clear evidence of relevant understanding. Science Centres should have humour and be run with a sense of humour. Here again the 'Explainers' or Guides or Pilots or very important.

5) Small effects. Appreciating significance of small effects or phenomena shows they are appreciated as *conceptually* important though they are not *perceptually* dramatic. (Thus the Photoelectric Effect heralded Quantum Mechanics, and the precession of the perihelion of the planet Mercury was a key to Relativity. Though conceptually dynamite they are physically tiny. There are many such examples.)

6) Nothing: **happening.** Perhaps the most dramatic evidence of understanding is seeing significance in *nothing*. This is the point of experimental controls. We should widen the notion of *experiencing* phenomena, for in science a great deal comes from significant small effects and *nothing* happening. But only when the situation is understood; for it is essential to appreciate what should (or should not) have happened on alternative hypotheses to appreciate nothing.

We have suggested, that to assess effects of hands-on experience we may look for: (1) Being surprised by predictions that turn out wrong; or against the odds, are right; (2) Ability to draw analogies, or see links between what on the surface look like different kinds of phenomena; (3) To fill in gaps, of mechanisms or whatever, and invent what could be there but hidden; (4) to appreciate relevant jokes; (5) To appreciate *conceptually small* but *perceptually significant* effects; (6) To appreciate significance of *nothing happening.*

Beyond Hands-On Exploratories ?

We have admitted a danger of exploratory Science Centres trivializing science, and unfortunately many do just this. Should we, indeed, speak of a '*Science* Centre' that lacks the rigour of science? For as we have said science is a slow, often tedious and sometimes dangerous business

Explanatories

As we have said: looking at the traditional museums of science, we find remarkably little science. There are very few explanations or examples of *methods* of science. It is hard to find Kepler's or Newton's Laws; or how spectral lines may be related to atomic structure; or concepts of Quantum Physics or Relativity. This general lack extends to technology. It is quite hard to find explanations of how motors, or radios, television or freezers work. Yet, technology can be exciting as *successful* experiment that reveal general principles.[4] Is it simply that science museums seldom attempt explanations because this is not their traditional aim or purpose? Or have they have found it almost impossible to present ideas in a museum context? Are the concepts and principles just too hard to present, without the kind of background knowledge, instilled over years in courses in schools and universities? This is an important question. It may be answered by seeing how far Hands-On science

---

[4] To give a recent example; it is a most imaginative concept to use a microscope *backwards* to shrink design drawings into working integrated circuits (and even minute motors and tiny geared mechanisms) with components as small as nerve cells of the brain. And now we can actually see electron charges moving through the logic gates of micro-chips, with a beam-switched scanning electron microscope, strobing repeated signals to slow things down to speeds we can see - which takes us right inside Alice's wonderland by technology.

can be pushed towards explanatory concepts. But can we interact with *abstractions,* hands-on? Perhaps we need to add to Exploratories, somewhat separate more thoughtful '**Explanatories'.**

Possibly existing schools and universities *are* the Explanatories we need. But in schools and universities explanations are built up gradually, on a carefully planned slowly growing basis of knowledge. Can we speed this up? Can we introduce sometimes difficult and counter-intuitive concepts, of physics, chemistry, life, symbols or whatever - in *minutes* rather than years? This is the challenge. Possibly only a few people will wish to take the step from the familiar assumptions of every day life into the non-intuitive, even bizarre concepts of science. But surely many people, of all ages, will find it incredibly exciting; even to giving new meaning to their lives.

How can we explore *abstract* concepts, hands-on? Some essential principles can be experienced directly by removing contaminating effects. Indeed, this is how many experiments have lead to discoveries. Less direct, but vital for moving from particular instances to principles, is providing a wide variety of examples – so that *general principles* emerge. Perhaps familiar technology can help to introduce unfamiliar, strange ideas of science

New technologies of data search could be useful for Eplanatories. Interactive computer-video disc technology can provide explanations, and allow individual journeys through facts and abstract concepts. But even apart from the expense there are problems to solve. For example, it is important to approach the same facts or ideas from different starting points - when they may appear in a different light - or remain dark! For this and for reasons of economy, many of the same pictures and descriptions will appear in different "journeys

"Handle-Turning" mathematics

Finally, should interactive Science Centres introduce what is for many people difficult and intimidating: *Handle-Turning* mathematics? Here, computers can come to the rescue. They remove so much of the sweat and tears of 'handle-turning', and their graphics reveal to the eye abstract principles and functions, with great beauty. Then, computers can be linked to actual experiments, to show mathematical functions and underlying principles operating beneath appearances in real time.[5]

It has even been suggested - by Philip Davis and Reuben Hersh in **The Mathematical Experience (**1980) - that computer interaction allows dimensions beyond the three of space and one of time, that we normally experience, to be visualized. A Rotating, computer-generated hypercube looks meaningless; but upon taking up the controls:

I tried turning the hypercube around, moving it away, bringing it close, turning it around another way. Suddenly I could *feel* it! The hypercube had leapt into palpable reality, as I learned how to manipulate it, feeling in my fingertips the power to change what I saw and change it back again. The active control at the computer console created a union of kinesthetic and visual thinking which brought the hypercube up to the level of intuitive understanding'.

This is truly turning minds on hands-on.

Conclusion

For some people making decisions by methods of science is alien, even dehumanizing. Perhaps they see scientific method (which objectifies judgements) as conferring a kind of *artificial* intelligence to human beings; even to turning us into machines. Although it may be admitted that science and technology transcend political and racial boundaries, and confer many undoubted benefits, this is not how many people want to see the world. Is this because science has been inadequately presented? Or is it because science is unable to answer questions that people see as important for their lives? Scientific method can be too slow to provide reliable answers in real-time, for individual and government decisions. These may all be true; but most people simply lack the understanding to have a comfortable, intuitive feel for science and their every day technology.

It may be that formal mathematics has too much prestige and over-dominates science education; as it intimidates so many people, to put them off science. Although "Hand-Waving" non-formal accounts generally have a rather low standing, it may be that they are very important for giving context to facts; for remembering and structuring experience into knowledge.

Discovering how to help children and adults explore phenomena, and appreciate principles effectively, must keep Exploratory Science Centres re-inventing themselves - to become viable mutations in futures they help to create. In our 'handy' terminology, surely they will succeed richly when they stimulate curiosity with *hands-on* experience, and give understanding through useful though informal *hand-waving* explanations - leading a few to *handle-turning* skills of mathematics.

This is introducing science, by shaking hands with the Universe.

References

Bacon, Francis (1620) **Novum Organum** (ed. F H Anderson). (Indianapolis (1960).

Bacon, Francis (1627) **New Atlantis.** (Oxford: OUP (1915)).

---

[5] This is the basis of Seymour Papert's work (Papert 1980) on Logo, in which the computer controls a mechanical tortoise which interfaces the object world with the symbolic world of mathematics.

Churchland, Paul M.(1989) **A Neurocomputational Perspective: *The Nature of Mind and the Structure of Science.*** (Boston: MIT Press).

Davis, Philip J. and Hersh, Reuben (1980) **The Mathematical Experience. (**Boston**:** Houghton Mifflin).

Driver, Rosalind; Guesne, Edith; Tiberghien, Andre` (xxxx) **Children's Ideas in Science. (**Oxford: OUP).

Gregory, Richard. L. and Wallace, Jean (1963) **Recovery from Early Blindness: A Case Study** Exp. Psychol, Soc, Mongr. II, Heffers, Cambridge. (Reprinted in: Gregory R..L. (1974) **Concepts and Mechanisms of Perception** pp. 65-129, London: Duckworth.

Gregory, Richard L. (1970) **The Intelligent Eye** London: Weidenfeld.

Gregory, Richard L. (1983) The Bristol Exploratory - A Feeling for Science' **New Scientist** (17 November) 484-489.

Gregory, Richard L. (1986) with contributions by: James Dalgety and Francis Evans, **Hands-On Science: An Introduction to the Bristol Exploratory,** London: Duckworth).

Gregory, Richard L. (1988) 'First-Hand Science: The Exploratory in Bristol', **Sci. publ. Affairs, 3,** 13-24. London: The Royal Society.

Held, Richard, and Hein Alan, (1963) 'Movement-produced stimulation in the development of visually guided behaviour', **J. Comp. and Phys. Psychol. 56 .**

Hodgkin, Robin A. (1985) **Playing and Exploring**, New York: Methuen.

Matthews G B (1980) **Philosophy and the Young Child**, Cambridge Mass. HUP.

Murphy, Pat (editor), (March 1985) **The Exploratorium:** Special Issue.

Oppenheimer, Frank (June 1979) 'Everyone is you . . . Or me' (Reprinted in: Murphy op. cit.).

Piaget, Jean, (1929) **The Child's Conception of the World** (J. and A. Tomlinson transl.) London.

Piaget, Jean (1955) **The Child's Construction of Reality** (Margaret Cook transl.) London.

Piaget, Jean (1952) **The Origins of Intelligence in Children.** New York.

Papert, Seymour (1980) **Mindstorms: Children, Computers, and Powerful Ideas.** Basic Books.

Pizzey, Stephen. (1987) **Interactive Science and Technology Centres** Science Projects Publishing, 67 Eccles Road London. SW 11.

Price, Derek de Solla (1974) **Gears From the Greeks: The Antikythera Mechanism.** *A Calendar Computer from ca. 80 BC,* New York.

Sambursky, S. (1962) **The Physical World of Late Antiquity.** (London: Routledge and Kergan PaulAntiquity).

Sarton, G. (1952) **Ancient Science Through the Golden Age of Greece.** (New York: Dover). .

Shortland, Michael (1987) 'No business like show business'. **Nature,** Lond. **328,** 213..

Valvo, Alberto (1971) **Sight Restoration Rehabilitation**, (American Foundation for the Blind, 15 West St., New York).