Chapter 7
The Learner's Thinking

This chapter will explore what is to be understood by our everyday term 'thinking' in research in science education. This account will build upon the earlier chapters in this part, by discussing thinking in the context of the 'cognitive system' of an individual learner. Thinking is a term used for a *mental* process (see Chap. 3) and so according to the analysis offered earlier in the book relates to personal subjective experience ('thinking' is part of what was called the 'mental register' in the part introduction) and is not available as an object for direct 'objective examination'. Indeed, a key theme that will be stressed in this chapter is that much of what is of interest to science education researchers in terms of learners' thinking is not solely related to those conscious processes that are open to report following introspection. Establishing this general feature will be important in setting out a background for the subsequent parts on student knowledge (§3) and learning in science (§4).

A Study on 'Scientists and Scientific Thinking'

Coll, Lay and Taylor report a study on '*Scientists and Scientific Thinking*' (Coll et al., 2008). They reported that 'the interviews provide a window into scientific thinking as practiced by modern scientists, and suggest that the scientists are rather more open to alternative thinking than might be supposed' (p. 197).

The study involved an initial administration of a set of statements that participants were asked to rate in terms of whether they believed they were true or false, followed up by in-depth interviews. This is an interesting study, which would bring into question any stereotypical view of scientists *necessarily* having beliefs (commitments to how the world is; see Chap. 6 and also Chap. 15 for a discussion of worldviews) that would exclude the existence of ghosts, UFO sightings, the possibility of prayer leading to healing, or health-improving effects of crystals.

However, the interest for present purposes is in the way that the notion of scientific thinking was used. As with many studies that focus on everyday notions

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such as 'thinking', the authors (Coll, Lay and Taylor) do not feel it necessary to offer a technical account of what they mean by 'thinking'. The terms 'thinking' and 'scientific thinking' are treated by the authors as unproblematic (their discussion draws on the 'mental register') and are apparently assumed to have a clear meaning for readers. In this volume, I am suggesting that scientific investigation of mental 'phenomena' (such as learning and thinking) requires us to conceptualise these mental phenomena in terms of cognitive systems (Chap. 3), and that thinking is the term used at the mental level that best links to *the processing* of information in the cognitive system. Some of the uses of the term in Coll and colleagues' paper would seem to fit with this meaning:

> Some personal experiences were seen to influence the scientists thinking about beliefs, making them at least potentially believable. (p. 204)
>
> It was noteworthy that some scientists 're-worked' some of the items presented in the surveys, thinking on their feet and seeking alternative explanations. (p. 209)

In these two uses, the authors seem to be referring to thinking in the sense of mental processes. However elsewhere, the term thinking refers less to the process than to the outcome of that process (with the present author's *emphasis*):

> Similarly, anecdotal evidence from "fairly stable sorts of people" was seen as a basis for *thinking that* some houses might be haunted… (p. 208)
>
> Such thinking also applied to the scientists' perceptions of our understanding of the brain, with many of the scientists *thinking that* there remains much unexplained about the brain – thus they were open to alternative explanations including paranormal phenomena. (p. 210)

It is widely accepted that word meaning is partly determined by context, and the shift in how 'thinking' is used here, although perhaps not ideal in a research report is understandable given the way the term is used in everyday life.

The more specific term 'scientific thinking' seems to be used in a different way in the paper. The subtitle of the paper refers to 'understanding scientific thinking through an investigation of scientists [sic] views about superstitions and religious beliefs', which would seem to imply that 'scientific thinking' refers to an aspects of the individual scientist (who holds view and beliefs). Yet in the body of the paper, the term is used rather differently (again, with my added *emphasis*):

> The panel of experts consisted of scientists across a range of disciplines that examined each item statement in the instruments and asserted that it was *in conflict with current scientific thinking* in that discipline. (p. 201)
>
> Likewise, the few that were less sceptical about astrology like Judy, thought that there were, potentially, underlying theoretical reasons *not inconsistent with current scientific thinking*… (p. 208)

Here 'scientific thinking' does not seem to refer to a process or product of cognition in individual scientists, but rather is considered to be linked to the scientific community: that is, presumably thinking that is consistent with current scientific knowledge. Here the authors are again using language in a commonly acceptable way. However, this does seem to raise a significant question of *what we might mean by the thinking of a community*. I have argued that thinking is the mental level description of the cognitive processing that occurs within an individual cognitive system (i.e. the individual, knowing subject, described at the cognitive system level), which in turn can ultimately be considered to arise from electrochemical activity within the brain of that individual. To shift to a community perspective would require considering the *overall* possessing activity in/across the network of cognitive systems.

This is a challenge that needs to be addressed. However, it is also pertinent to note that the way Coll and colleagues refer to scientific thinking here makes it clear they are not primarily referring to the process (i.e. processing) itself, but the outcomes of that process: the ideas and evaluations that are products of the process. So, for example, a view about whether some crystals might have inherent healing properties would be a product of thinking processes. For this reason, this issue will be deferred to a later chapter (Chap. 10), where the nature of scientific knowledge will be discussed.

Coll and colleagues' paper offers a useful insight into the outcomes of the thinking of some scientists about a range of topics, to test the notion that scientists would adopt a kind of 'party line', and so take on consensual positions, on certain issues. It therefore makes a useful contribution to scholarship. Some of the data presented does offer indications of aspects of the thinking processes of the participants, but generally the study is concerned not with scientific thinking (as a process) but more with the *outcomes of* scientists' thinking about focal topics.

This is not a peculiarity of the way Coll and colleagues use the term 'thinking'. A study on explanation in science classes by Braaten and Windschitl (2011) includes both of the following statements:

> The term "explanation" is also used to connote the communication of reasoning in an effort to make thinking visible or audible in science classrooms. (p. 654)
>
> In science classrooms, it can be difficult, if not impossible at times, to provide students and teachers with sufficient access to theory and evidence to allow for reasoning through alternative explanations to ultimately arrive at an understanding consistent with current scientific thinking. (p. 665)

The first of these quotations talks of making thinking visible or audible – something that it was earlier argued was problematic, and seems to refer to *the process* of coming to a view or judgement. However, the phrase 'understanding consistent with current scientific thinking' seems to refer to the outcomes of thinking, rather than the processes by which these outcomes were reached.

Establishing a Meaning for 'Thinking'

Thinking has understandably been an important concern in science education, one purpose of which is said to be to facilitate the development of 'scientific thinking' among learners (Laugksch, 2000; Lawson, 2010; Lehrer & Schauble, 2006). However, thinking is one of the terms that (as highlighted in Chap. 3) are used as an everyday label for something which is understood in a non-technical sense – that is, it is a phenomenon of the lifeworld, part of the mental register of our folk psychology.

> But what is thinking? This might seem a pointless question, since everyone knows by acquaintance what thinking is from his own first-hand experience of doing it…Very few people ever think about thinking. It is one thing to practice an activity and quite another thing to stand back and try to observe, describe, and account for that activity. It is one thing to realize that certain activities happen, but quite another thing to take special steps to show precisely what does happen and how it happens in the way it does. (Thomson, 1959, pp. 12–13)

Thomson goes on to suggest that there are at least six ways in which the term 'think' is used in normal discourse. So people may refer to daydreaming, recalling, deliberate imagining, concentrating and their opinion or reasoning when reporting what they think. Similarly, another commentator notes that the term 'thinking' 'is used to cover reasoning, conceiving, imagining, perhaps day-dreaming, though rarely dreaming proper' (Aaron, 1971, p. 91). As suggested earlier in the book, this is not a problem in everyday conversation, as context usually suggests intended meaning, and we can interrogate the speaker if unsure. However, this book is concerned with conceptualising and reporting research in science education, and if research literature is to be properly understood so it can be built and acted upon, it is important that when research results are reported, they use terms that have been explicitly operationalised.

In Chap. 3, an approach to describing cognition, which would include thinking, at three levels was presented (see Table 3.4). It was argued that these three levels of description are complementary – that mental activity such as thinking can be understood in terms of cognition as processing activity within a cognitive system, that in turn could be in principle explained in terms of electrochemical processes in the nervous system and in particular the brain.

Normal everyday conversation focuses on the mental level of description – considering 'ideas' and 'thoughts'. At this level we might consider that thinking is the activity that leads to ideas: thinking is a *process*, and ideas or thoughts are the mental *'products'*. There is nothing wrong with this level of description for some purposes, including much everyday conversation. However, as introspection only offers a very limited appreciation of the nature of thinking, this may not be sufficient for research purposes.

Thinking and Processing

In terms of the ways cognition has been represented in previous chapters in the book, there is a key issue in how we understand the relationship between the systems-level description of processing within the cognitive system and thinking as a mental phenomenon.

This is recapped in Fig. 7.1, which shows a model of the key stages of processing information within the cognitive system. Conscious thinking is considered to be a correlate of processing in some executive module of the system (see Chap. 3), usually identified with working memory (see Chap. 5). However, if we consider the

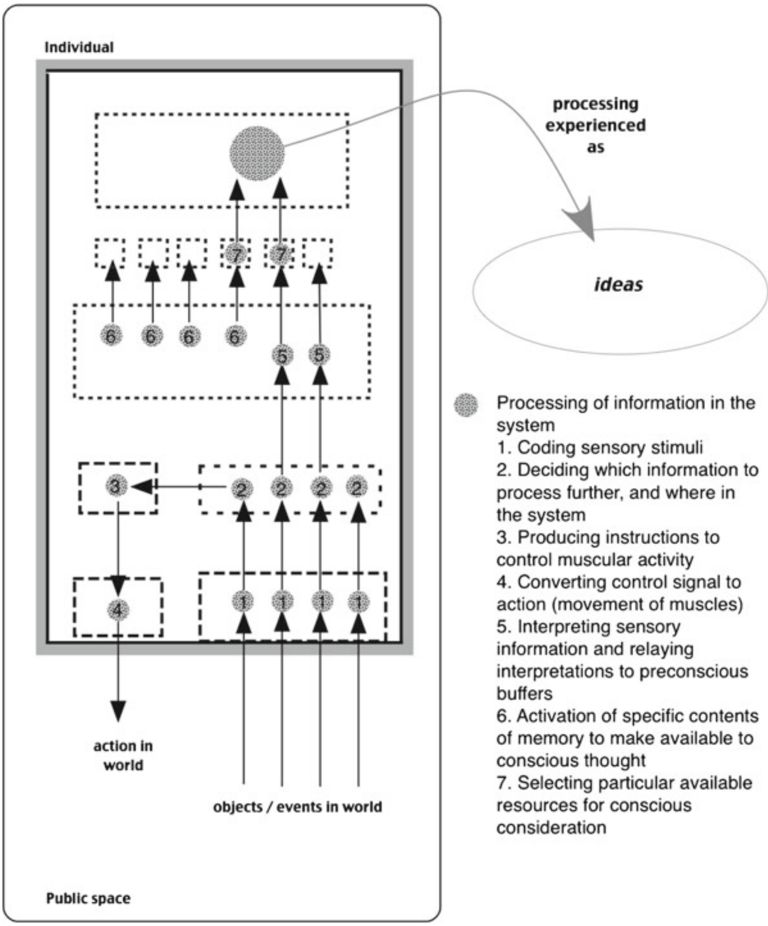

Fig. 7.1 Processing and thinking – recap of discussion of processing in the cognitive system in earlier chapters

cognitive system to be the basis of intelligent behaviour, then much processing below the conscious level contributes to this. Arguably even reflexes are a form of intelligent – certainly adaptive – behaviour, even though the processing of information, decisions about action and control of that action (blinking, moving a limb, etc.) all take place without conscious involvement. Yet, in general conversation, we would not normally call that level of processing ‘thinking’.

Indeed references to such phrases as ‘processing below [sic] the conscious level’ impose a topological metaphor reflected in figures such as those I have used in this volume that might seem to reflect or imply a notion that what goes on at a ‘lower’ level is less important. However, at the very least, it is clear that conscious thought is facilitated and underpinned by cognitive processing that the individual is not conscious of. Indeed, to use another metaphor, conscious thinking is ‘just the tip of the iceberg’.

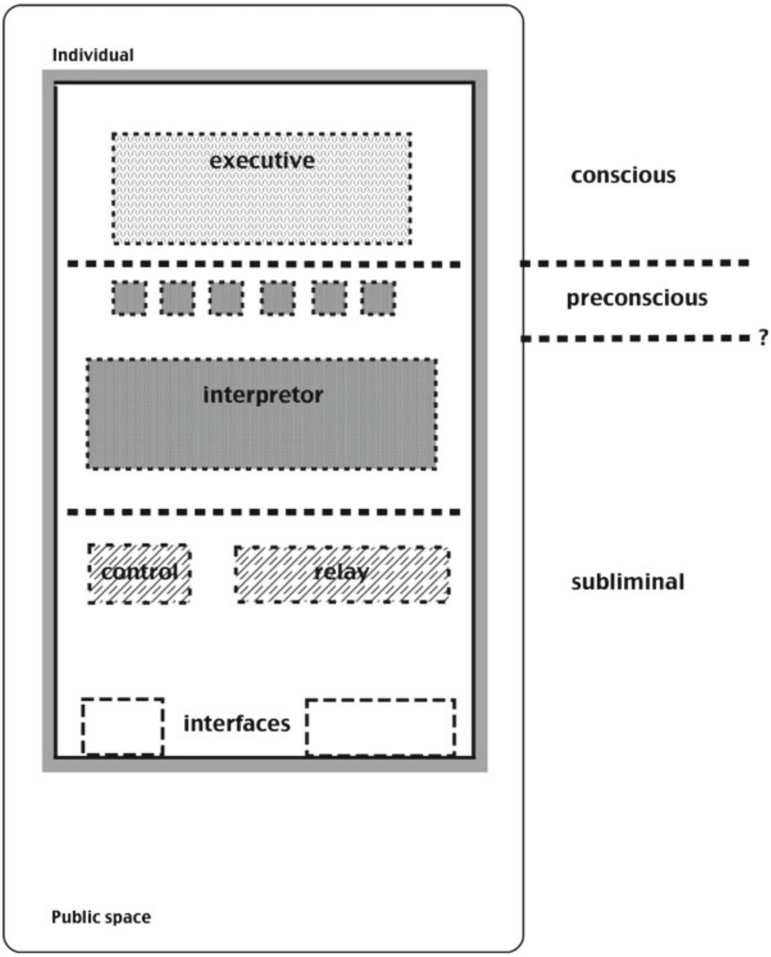

Fig. 7.2 Levels of processing in the cognitive system

If we consider the distinction between conscious, preconscious and subliminal processing (introduced in Chap. 4), then we can consider the cognitive system to be divided as in Fig. 7.2.

If we argue that the module concerned with conscious thinking (perhaps working memory; see Chap. 5) is the executive, then we could extend this organisational metaphor to other aspects of the system. We might think of the interfaces as being routine operations that are the 'unskilled' sector of the system, where work is carried out mechanically. The subliminal level at which filtering and control of information is undertaken is in this analogy a more technical level, with decisions being made as if according to an established code book, with problematic cases 'referred upstairs' for higher-level consideration. At the preconscious level is the professional/managerial work. Here – in terms of this analogy – incoming information is interpreted, and reports are presented with recommendations for possible courses of action. These reports are selectively attended to by the executive, which relies on the work of its professional part to provide accurate accounts and to suggest creative scenarios and options. Whilst such a metaphor is clearly only meant to offer some heuristic value, it does reflect how a good deal of important processing takes place prior to any conscious awareness and how the effectiveness of conscious thought is limited by the quality of the information provided by preconscious processes. *It would seem perverse to exclude this level of processing from being considered 'thinking'*.

The Significance of Preconscious Processing

So the processing which correlates to *conscious* thought may only be one stage of a more complex sequence of processes, much of which we are never aware of consciously. Were these subconscious processes limited to general physiological regulation and reflex actions, and so involved something largely unrelated to conscious thought, then we might feel it is useful to reserve the term 'thinking' for conscious processes. However, this does not seem to be the case.

I would suggest that the activity of the crossword puzzle offers a useful insight into the limits of conscious awareness during thinking. My own experience here is that some clues lead to a possible answer appearing immediately in consciousness; others do not, but I am often able to get an impression of whether I am going to be able to readily think of the answer – even though I do not at that moment have one 'in mind'. Sometimes I have the impression that I have nearly got the answer, and I am just waiting for it to appear in consciousness, although I am not quite sure how to help the process along. This is a widely reported experience, known as the 'tip-of-the-tongue' phenomenon or a 'feeling of knowing' (Parkin, 1987, p. 37) – when someone finds they cannot (yet) produce the word they are 'looking for' although they are pretty sure it is in their vocabulary and *at some level* they 'know' which word they want to use.

This tip-of-the-tongue experience could be put down to wishful thinking or some kind of cognitive error, except that it often seems to be accurate: it is usually accompanied by the production of the word or answer that we then recognise as being what we were trying to access. It would seem that at some level of the cognitive system, we are able to recognise that the target of some kind of search process has been located, before we are able to form a representation of it at the level of processing which is associated with conscious thought. Perhaps this links to the issue of thinking largely being in a form of 'machine code' that then has to be expressed into verbal language (see the previous chapter, Chap. 6). So Brown and McNeill reported that when students were asked to identify words used at low frequency in the language from definitions, about half of the words generated before finding the word they considered matched the definition shared its initial letter (Brown & McNeill, 1966/1976). This suggests that the students were not just accessing semantically similar words as might be expected working from a definition, as these would more often than not have different initial letters.

This is just one example of how 'subconscious' (preconscious) processing is important for, and seems to blend into, conscious processing of information. Freud's work showed that much of our thinking seems to be subconscious – 'a sea of unconscious ideas and emotions, upon whose surface plays the phenomenal consciousness of which we are personally aware' (Hart, 1910, p. 365) – to the extent that, it is claimed, we often act on motivations that we do not consciously recognise leading to us finding alternative rationalisations to explain and justify our actions.

Various pathological conditions also support this type of argument. For example, people exhibiting the condition of blindsight have no visual awareness and consider themselves to be blind, although no physiological damage may be detected on medical examination. A person with blindsight cannot report what is in their visual field, because as far as they are aware, they do not have vision. However, they can be very good at 'guessing' what is in their visual field. So it seems that one part of their brain has access to the visual stimuli and is able to process the sensory impressions to the degree they are interpreted into what should be precepts (objects and so forth), but the visual images themselves are not accessible to consciousness. When asked to guess about objects placed in front of them, the blindsighted person is often able to report accurately, although as they have no conscious awareness of how they could know, they consider they are just guessing (Churchland, 1980; Gazzaniga, Fendrich, & Wessinger, 1994).

Thinking as an Inclusive Term

This suggests that to reserve the term 'thinking' for conscious thought would be a rather arbitrary distinction. So instead I will use the term 'thinking' to describe cognitive processes that are not necessarily conscious (see Fig. 7.3). That is not to suggest that reflex actions or automatic adjustments of posture which require some low level of processing in the nervous system should be considered as thinking; but rather processing that is considered to be related to cognitive activities such as

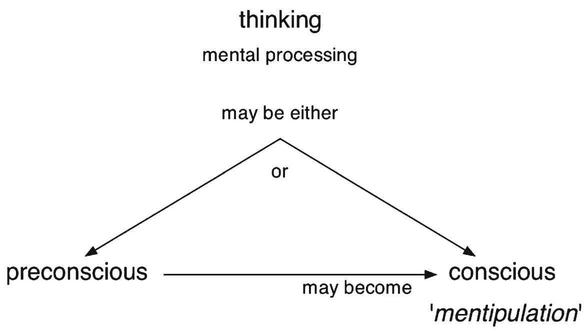

Fig. 7.3 Thinking is not necessarily conscious

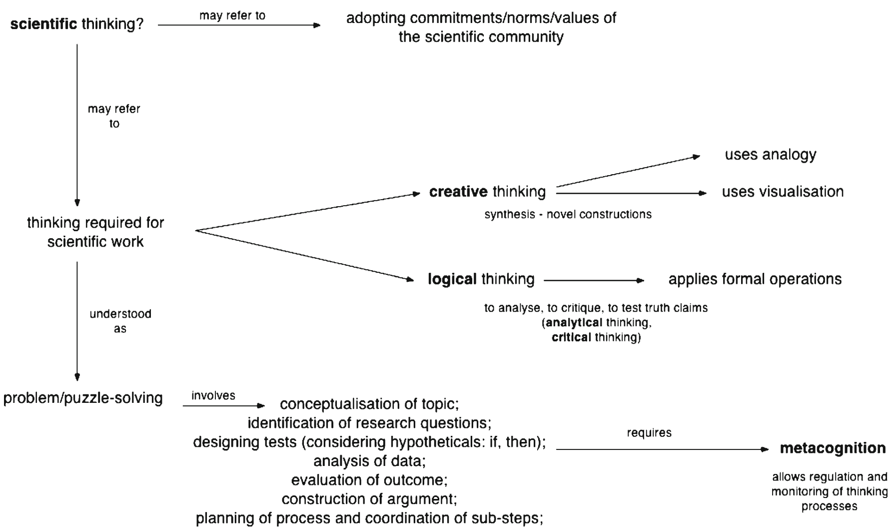

Fig. 7.4 Aspects of scientific thinking

concept learning and problem-solving will be considered as a kind of thinking, whether conscious or preconscious. Where it is important to differentiate, or to avoid being misinterpreted, the inclusive term ‘thinking’ can be qualified by being preceded with ‘conscious’ (or ‘preconscious’) as seems appropriate. Alternatively, the type of processing of information that is consciously experienced directly ‘in the mind’ could be termed mentipulation – that is, the mental analogue of manipulation (perhaps a rather obvious neologism to coin, and the term has previously been suggested by Ivić, Pešikan, & Antić, 2002).

Forms of Thinking Valued in Science Education

Traditionally, science education has been associated with the development of certain types of thinking styles or skills, and often this has been ‘logical’ or ‘critical’ rather than ‘creative’ thinking. However, science also involves creative thought, and creativity is important to learning in science (see Fig. 7.4).

Scientific Thinking

> Science is much more than a body of knowledge. It is a way of thinking. This is central to its success. Science invites us to let the facts in, even when they don’t conform to our preconceptions. It counsels us to carry alternative hypotheses in our heads and see which ones best match the facts. It urges on us a fine balance between no-holds-barred openness

> to new ideas, however heretical, and the most rigorous skeptical scrutiny of everything – new ideas *and* established wisdom. (Sagan, 1990, p. 265, emphasis in original)

One of the aims of science education is to help students develop 'scientific' thinking. As we saw earlier in this chapter, the term scientific thinking is sometimes used to refer to public scientific knowledge, that is, current scientific thinking about a topic.

It has also been characterised as the adoption of a scientific worldview, that is, a set of assumptions about the world that guide thinking (see Chap. 15). If thinking is for the purposes of this chapter considered a process, then these other meanings relate to either the outcomes of thinking (output) or resources to support thinking (input) and not the processing itself. Scientific thinking in these senses then lies outside the scope of this chapter, and these points are picked up in later parts of the book.

More commonly, scientific thinking can refer to the thinking processes required to undertake scientific work. Whilst it might be difficult to agree a definition of what scientific thinking is, it is recognised to be central to the practice of science. It has also been argued that 'scientific thinking is a paradigmatic example of cognition that reveals the key features of many basic cognitive processes' (Dunbar, 2001, p. 115). It has sometimes been strongly associated with the application of the 'scientific method'. In particular, it has been associated with rational, logical thinking (cf. Fig. 7.4).

Science-as-Logic: Logical Thinking

Logic has long been associated with a key form of thinking. Indeed, Bonatti has suggested that

> An old and venerable idea holds that logic is concerned with discovering or illuminating *the laws of thought*. Its psychological corollary is that a system of logic in the mind underlines our thinking processes. … In a nutshell, it holds that reasoning consists of operations on mental representations, according to logical rules implemented in procedures activated by the forms of the mental representations. (Bonatti, 1994, p. 17, present author's emphasis)

Logic is central to scientific work because designing and interpreting scientific investigations requires the application of particular types of general rules. These are involved in establishing the conditions under which it is appropriate to draw specific conclusions. So in school science, learners will be taught about control of variables and how to set up control conditions so that results will allow them (in ideal cases at least) to draw conclusions about whether a particular cause produced a particular effect (i.e. 'fair testing').

In practice, science is seldom as simple as it often tends to be represented in school science (Taber, 2008b). Rather, experimental design always depends upon both an existing conceptual framework that suggests which of the potentially infinitive range of variables might potentially be relevant (e.g. in exploring the effect of wire length on resistance, we might decide it is important to control for material and temperature; we may however consider that it is not relevant whether the wires are vertical or horizontal, whether they are aligned North–South or East–West, whether it is a Tuesday or a Wednesday, whether we have said a prayer before we collect data, whether the lab is on the ground floor, the gender or nationality of the lead researcher, what they had for breakfast and so on, ad infinitum) and a theoretical or methodological framework informing the choice of particular techniques which can collect valid and reliable data (Taber, In press).

However, whilst these considerations are of great practical importance, underlying any such investigation is a more fundamental framework (a metaphysical belief system; see Chap. 15) that says that science is possible because the world can be understood in terms of causes that bring about effects, and do so in regular ways (we assume there are ‘laws of nature’ that will not change from day to day or from one place to another), so that through setting up suitable combinations of conditions, we can determine necessary and sufficient causes by applying simple logical rules (Sijuwade, 2007). So, for example, we cannot claim that some factor is a necessary cause of some effect if sometimes we see the effect when that factor is not present.

The *Handbook of Child Development* refers to one image of science as being ‘science-as-logic’, where

> Science-as-logic emphasizes the role of domain-general forms of scientific reasoning, including formal logic, heuristics, and strategies, whose scope ranges across fields as diverse as geology and particle physics…These heuristics and skills are considered important targets for research and for education because they are assumed to be widely applicable and to reflect at least some degree of domain generality and transferability. (Lehrer & Schauble, 2006) p. 156

The authors of this review, Lehrer and Schauble, suggest that ‘learning to think scientifically’ is variously conceived of as:

- Acquiring strategies for coordinating theory and evidence
- Mastering counterfactual reasoning
- Distinguishing patterns of evidence that do and do not support a definitive conclusion
- Understanding the logic of experimental design (p. 156)

These rules of logic often seem self-evident to researchers, so that conclusions can be drawn from data without having to explicitly refer back to them. Yet Dunbar (2001, p. 116) notes that ‘much cognitive research and research on scientific thinking has demonstrated that human beings are prone to making many different types of reasoning errors and possess numerous biases’, and that ‘informing subjects of these biases does little to improve performance, and even teaching subjects strategies for overcoming them does little to ameliorate these biases either’. He goes on to suggest that ‘much research on human thinking and reasoning shows that thinking is so error-prone that it would appear unlikely that scientists would make any discoveries at all!’ Yet clearly some of the population are either less prone to these logical errors or alternatively are able to learn to overcome them – at least in their professional work. Making the logic of scientific investigation more explicit in school science may be important here (Lawson, 2010), especially where what seems self-evident to the teacher is being missed by the learners.

Indeed, the very notion that the human brain has innate apparatus for logic has been questioned. Bonatti (1994, p. 17) suggests that 'even if the thesis loomed around for centuries, there is still little convincing psychological evidence of the existence of a mental logic'. An important difference here might be between a logical analysis suggesting how scientists ought to think; and psychology, which tells us that we fall short of the ideal (Nickerson, 1998). Presumably such imperfections are the result of natural selection pressures, because some logical corner cutting is often the pragmatically more effective approach in dealing with the everyday problems of survival. After all, when faced with food shortages or dangerous predators, a weakly supported plan of action that can be implemented now might often prove to be better than a well-researched plan of action that we are hoping to have ready at some hypothetical point in the distant future.

Creative Thinking

Creativity is a central part of doing science, and one criterion by which scientific work is judged is that it shows originality. Indeed creative and logical thinking are complementary prerequisites of scientific discovery (Taber, 2011). Arthur Koestler (1978/1979) argued that science, art and humour all relied on the same creative processes of bringing together previously unrelated ideas into a new juxtaposition. Although scientific work does require logic to devise and interpret tests of ideas, it also relies upon someone producing the idea that will be tested. How we have such novel ideas is not well understood. Whereas, in logical thinking, conclusions are in a sense already implied by the premises; creative thinking means coming up with something that goes beyond the information available and that is not logically justified. In creative thinking there is no set procedure or set of steps to follow, and often an idea just appears in consciousness. Indeed, there are many stories of how creative thinking is best supported by relaxed distraction (Taber, 2011) – taking a bath, dozing, going for a walk, etc. – albeit usually after an extended period of intense engagement with the problem area being studied. Plant geneticist and Nobel laureate Barbara McClintock talked of how her brain would 'integrate' information in the background and come up with possible solutions to scientific problems (Keller, 1983):

> I read the paper and when I put it down I said, 'This can be integrated'. My subconscious told me that. I forgot about it, and about three weeks later I went into the laboratory one morning at the office. I said 'This is the morning I'll solve this'. (Quoted in Beatty, Rasmussen, & Roll-Hansen, 2002, p. 282)

This might be described as relying on intuition or tacit knowledge which has been developed but which is not consciously available (see Chap. 11). Einstein is commonly quoted as suggesting that 'the intuitive mind is a sacred gift and the rational mind is a faithful servant'.

It seems sensible to assume that creative ideas or problem-solutions that seem to appear suddenly in mind are actually the outcome of processing within the brain outside of conscious awareness (see Fig. 7.5). That is, thinking is occurring that is

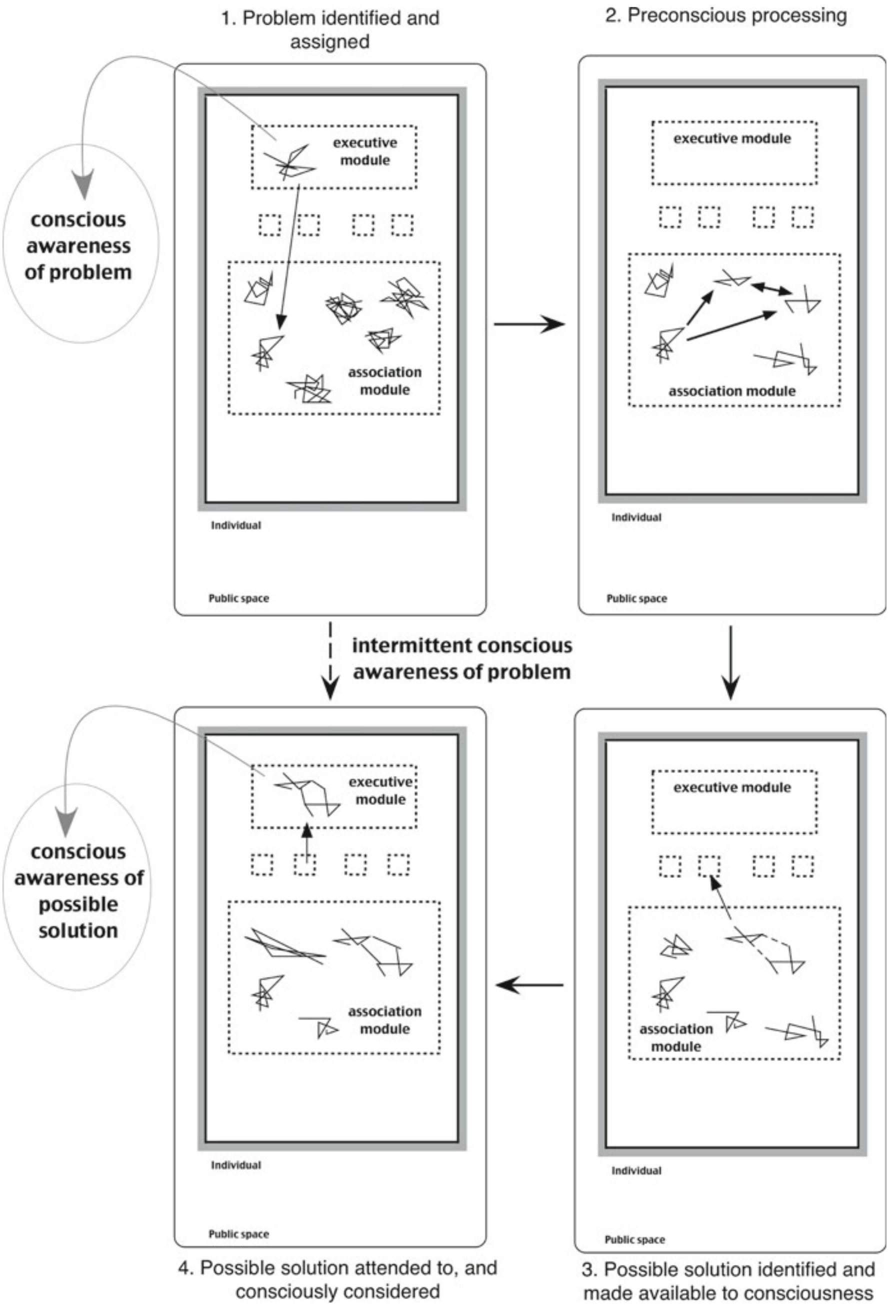

Fig. 7.5 We can consider the executive component of the cognitive system to assign (problem-solving, creative) tasks to preconscious processing and then later to accept reports

inaccessible to consciousness, but is still goal-directed, and often motivated by known problems and issues previously considered in conscious thought. Baddeley (2000) has suggested that the component of working memory (i.e. the executive module of the cognitive system; see Chap. 6) that he labels the episodic buffer may have a role to play here in creating new cognitive representations, that is, new syntheses from, or modifications of, existing available representations.

Extending the analogy used earlier, we might think of the executive referring an issue to some kind of working group to consider, for later report. Whilst the analogy should not be given too much weight, it does seem that this type of delegation/assignment of processing to preconscious levels is a key part of much human cognition.

Changeux has suggested how such processes may be understood in terms of physiological properties at the physical level (see Chap. 3):

> The neurons participating in assemblies of concepts will be both dispersed and multimodal, or perhaps amodal. This should bestow on them very rich 'associative' properties, allowing them to link together and above all combine… This recombining activity would represent a 'generator of hypotheses', a mechanism of diversification essential for the genesis of pre-representations and subsequent selection of new concepts. In a word, it would be the substrate of imagination. It would also account for the 'simulation' of future behaviour in the face of a new situation. (Changeux, 1983/1997, p. 169)

Analogical Thinking

Analogy has been proposed as one major source of creative ideas in science (Muldoon, 2006). Wong argues that 'analogical reasoning is one means by which experience is related to and differentiated from what is already known. Through analogies, an understanding of novel situations may be constructed by comparison to more familiar domains of knowledge' (Wong, 1993, p. 1259). According to Gentner (1983, p. 159), 'an analogy is a comparison in which relational predicates, but few or no object attributes, can be mapped from base to target'. She gives the example of the analogy that a hydrogen atom is like our solar system, where it is intended that relations are mapped from the solar system to the atom (e.g. the *electron* orbits the *nucleus*, like the *planets* orbit the *Sun*), but not object properties (e.g. not that the *Sun* is yellow, so the *nucleus* is yellow).

Analogical thinking can therefore be a component of creative thinking, as by considering that X could be like the more familiar Y, possible features of X are suggested which can then be subject to testing. Analogical thinking would seem to involve at least two separate processing tasks: first searching through representations of the familiar to find a possible analogue for the target to be better understood by recognising some form of similarity and then undertaking a formal mapping process to see what the analogy would suggest may be the case about the target. When 'teaching analogies' are presented in class (Harrison & Coll, 2008), the learners are faced only with the second (analytical) part of this process, whereas when learners are asked to generate their own analogies (Wong, 1993), they must also undertake the initial step of finding a source analogue that offers some kind of similarity to the target.

The mapping exercise is undertaken with full conscious awareness: decisions are made about how aspects of the analogue map to the target and are open to conscious evaluation before being represented in the public space to communicate the analogy to others. The search process, whilst initiated with conscious awareness, would seem to be largely undertaken by processing that occurs below the level of conscious awareness, so that we become consciously aware of a limited number of possible candidate analogues and are not aware of the vast number of other potential analogues represented in the cognitive system which are judged at a preconscious level not to offer any similarity and so not worthy of further consideration. This process would seem to be an example of the type of cognitive work that largely takes place without our being able to (consciously) access and monitor the process itself. Rather, we just have access to its 'outputs' (see Fig. 7.5).

Imagery

In Chap. 6 it was suggested that our thinking does not occur primarily in verbal language, rather that 'thought is to some extent independent of the capacity to handle a language' (Anderberg, 2000, p. 110). Clearly, as modern humans, much of our *conscious* experience is in the form of verbal language, and language acquisition certainly provides important tools for internal conscious thought (Vygotsky, 1934/1986) just as much as for communication between minds (Vygotsky, 1978). Moreover, part of the 'executive' processor associated with conscious thought (the phonological loop in working memory; see Chap. 5) seems to have evolved to facilitate this. However, this executive module is also thought to include what is labelled the visuo-spatial scratch pad, which provides representations in imagistic form. As Baddeley points out, 'there are many examples of the importance of visual or spatial imagery in scientific discovery, including Einstein's development of his general theory of relativity' (2003, p. 834).

Einstein is just one of a number of scientists who have described how much of their creative thinking was imagistic (Miller, 1986). Nersessian (2008) has described how scientists form mental models, often represented in images, which act as mental simulations that can be 'run' so that the outcomes can be compared with the target phenomenon. Kekulé famously described a kind of exploratory imagistic simulation when he claimed to have had the idea that the benzene molecule was cyclic after interpreting an image of a snake grabbing its own tail:

> I turned the chair to face the fireplace and slipped into a languorous state. Again atoms fluttered before my eyes. Smaller groups stayed mostly in the background this time. My mind's eye, sharpened by repeated visions of this sort, now distinguished larger figures in manifold shapes. Long rows, frequently linked more densely; everything in motion, winding and turning like snakes. And lo, what was that? One of the snakes grabbed its own tail and the image whirled mockingly before my eyes. (as quoted in Rothenberg, 1995, p. 425)

The ability to imagine in this way is thought to make use of the same areas of the brain that are involved in visual perception (cf. Chap. 4). That is, the cognitive system includes apparatus for producing visual images, presumably evolved initially for converting sensory information to visual percepts, which are also (i.e. during evolution, have been recruited to be) used to generate visual images from processing initiated internally within the system – when remembering or imagining (Changeux, 1983/1997; Parkin, 1993).

Given the suggestion that there may be rare individuals who as adults retain eidetic imagery ('photographic memory'), when most people have very limited visual working memory (see Chap. 5), it seems possible there may be quite significant variations in the capacity of individuals to mentipulate visual images – and this may be one area where individual differences between science students may be quite significant in determining cognitive styles and mental capabilities.

Critical Thinking

Another descriptor often associated with scientific thinking is critical thinking (Lindahl, 2010) which has been described in a consensus statement from a Delphi study as 'purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which that judgement is based' (Facione, 1990, p. 3). Critical thinking has been associated with the ability to make decisions in complex situations or to find solutions to weakly structured problems (Lubben, Sadeck, Scholtz, & Braund, 2009).

That is, whereas logical thinking can be analysed in terms of following certain rules (e.g. effectively 'if/then' rules, albeit often nested in complicated ways) – such that providing the structure of rules is followed correctly and assuming the information provided was accurate, then the 'right' answer will be obtained – logic alone is insufficient when the 'ifs' remain 'iffy'. This is a more realistic scenario for most real-life decision-making as there is seldom a full, unambiguous data set to support a single assured solution to real-life problems.

Problem-Solving

Problem-solving is widely recognised as a key concern of education, and indeed Lawson and Wollman (1976, p. 413) report that according to the Educational Policies Commission, 'the central purpose of American education is the development of problem-solving processes called rational powers'. Problems, by definition, do not have ready solutions, and in an educational context, a problem is something that a learner is *not* able to solve by simply applying a familiar routine: as Jonassen (2009, p. 17) suggests '…problem solving entails a lot more cognitive activity than searching long-term memory for solutions'. What is a problem for one person who is a novice or less advanced learner may be straightforward to another who is a more advanced learner or an expert. Therefore judgements about what count as a problem have to be made relative to specific learners (Phang, 2009).

As an example of this point, consider the example of a teacher asking a secondary student to complete the following word equation:

$$\text{nitric acid} + \text{potassium hydroxide} \rightarrow \text{-------------} + \text{water}$$

This is a trivial task for chemists, chemistry teachers and advanced students. Indeed, if the author is given a task such as this, then the answer appears in consciousness without any explicit attempts to work out an answer, much quicker than I can formulate the rationale for why the answer is potassium nitrate. Yet for many secondary students, this task, which certainly has the appearance of a simple exercise to the teacher, takes on the nature of a problem, as the student has to seek out relevant knowledge and a way of coordinating that knowledge to produce a candidate answer (Taber & Bricheno, 2009).

Problem-solving, then, is a special kind of creative thinking, in that the individual has to find some new synthesis that although perhaps well known to others is a novel association for that individual. Problem-solving is believed to be an area where the limitations of working memory capacity can restrict learner performance (Tsaparlis, 1994). It is also thought that successful problem-solving is dependent upon metacognitive processes.

Metacognition

Metacognition, cognition of cognition, involves thinking about one's own thinking and has been defined as 'knowledge of the processes of thinking and learning, awareness of one's own, and the management of them' (White & Mitchell, 1994, p. 27). The idea of metacognition is closely related to that of 'self-regulated learning' and in schools may be linked to 'independent learning skills' or 'study skills'.

A key point made above is that much cognitive activity occurs without conscious awareness; metacognition is concerned with conscious thinking about one's own cognition and how this can be used to plan, monitor, evaluate and redirect one's own thinking. Clearly then, in terms of the model of learner as cognitive system developed in this book, 'metacognition is closely related to executive function, which involves the ability to monitor and control the information processing necessary to produce voluntary action' (Fernandez-Duque, Baird, & Posner, 2000, p. 288).

This does not undermine the claim that much thinking is undertaken away from conscious awareness, rather it is *because* so much cognitive processing occurs at preconscious levels that metacognition becomes so important. For example, in Fig. 7.5, it is suggested that a problem that the individual is consciously aware of can be metaphorically 'assigned' to be worked upon preconsciously, and only once a solution has been identified does it get flagged to be made available to consciousness. However, the executive module is then able to decide whether to accept the solution as a basis for action (e.g. to represent it in writing on an examination script) or whether to continue the search for a better solution. So the suggested solution presented to consciousness needs to be seen as a proposal (if a course of action is sought) or hypothesis (if an explanation is sought) that can then be evaluated. Without the metacognitive 'layer', we could do, say, or be satisfied as an explanation with, the first thing that 'came into our heads' (i.e. was presented to conscious awareness).

This also links back to the complementary roles of creativity and logic in scientific discovery (Taber, 2011). When making claims to new scientific knowledge, the context of discovery is less important in persuading others than the context of justification. It should be of no relevance to the evaluation of the quality of our ideas whether they occurred to us in the bath, or when chatting with a colleague over coffee, or through a sudden insight of an analogy with a work of art we were inspecting. However, we must make a logical case based on evidence for why the idea should be taken seriously. Our metacognition allows us to consider if there are good grounds (the justification) for considering an insight (the discovery) to be correct or at least productive as the basis for further action.

In both problem-solving and scientific discovery, the creative step seems mysterious but is essential, and the logical work concerns evaluating the output of the creative stage. Scientific discovery may be associated with the public community of scientists and their outputs (see Chap. 10), but in terms of it depending on individuals processing information in their cognitive systems, it has parallels with a school student solving a problem or suddenly making sense of what the teacher is trying to explain. In both cases progress depends upon an insight that is the outcome of thinking that largely takes place outside of conscious awareness.

The Fallacy of 'Machine Code'

Before leaving the consideration of cognitive processing, it is useful to revisit one notion that was referred to earlier in the book. In Chap. 4, the way in which sensory information had to be 'coded' so that it could be processed in the cognitive system was considered. Information available from, for example, photons – quanta of energy – being incident upon, and being absorbed by retinal cells, is represented into patterns of electrical activation in the optic nerve. So retinal cells act as transponders that convert a signal of one kind into something different. The term 'coding' seems appropriate as perception of the external world is only possible because the cognitive system's sensory interface (see Fig. 4.2) converts the patterns of, for example, illumination, into patterns of electrical activity in a non-arbitrary way. This allows the information available to the senses to be interpreted by the rest of the cognitive system.

The Limits of Computing Analogies for Cognition

The notion of 'machine code' draws upon an analogy with electronic computers. These computers are basically extensive networks of binary switches (on or off), so all processing must be in terms of signals cuing switching between on and off states to initiate or stop signals elsewhere in the system. Yet programming was traditionally undertaken in 'higher-level' languages designed for that purpose, for example, using logical operations such as 'if/then', such as COBOL, ALGOL and BASIC. The instructions written in these higher order languages therefore had to be translated into the code used by the machine by a conversion process (known as compiling). We can understand what happens when sensory information is coded into the human cognitive system as being *analogous to* this. We should however bear in mind, as suggested above, the important proviso that analogies reflect notable parallels in structure within different systems, but this does not imply the target system is in all senses like the analogue.

Whilst use of early computers required writing programmes in one of the higher-level languages, and then using the compiler to translate into the machine code, the experience of modern computer use is very different for most users who use the computer as a tool and have limited interest in programming it themselves. The operating systems of modern personal computers have inbuilt programming that allows users to undertake a wide range of operations with user-friendly interfaces. So a file can be copied into a new folder without any knowledge of programming languages, simply by using iconic representations on screen, such as dragging an icon from one location to another with a mouse, touchpad or on the screen itself. As I tentatively suggested earlier, when we undertake these operations, we 'see' the icons as the files and folders they represent and conceptualise them as having the physical locations shown, and we can consider this in some ways akin *to* the role of consciousness in our own thinking: in using the computer the interface presents us a simple visual representation of the 'world' inside the computer that allows us to operate on (in) that world effectively because the representational system becomes that world to us. The extent to which we are aware that we are only operating with a representational interface, and understand how what we do with the icons relates to aspects of computer architecture, might be seen as akin to metacognition, allowing us to reflect upon our use of the interface and perhaps better think through problems when the systems do not seem to be doing what we want or when we wish to undertake an operation we are not familiar with. Many people, however, use computers without reflecting on these issues, lacking the (analogue to) metacognition to move beyond a kind of phenomenological experience where the desktop *is* the working space and the icons *are* the folders and files they represent.

A Different Type of Processing System

At one level, this is a strong analogy. It is clear that the processing in the brain is in a form of 'code' that is not the same as sensory input data (it clearly cannot be – light and sound do not travel into the cortex), nor is it the same as our conscious experiences, as pointed out earlier in the chapter. However, there are some significant differences between human cognition and electronic computers that we must be aware of when using such an analogy.

One important difference is the nature of the processing. An electronic computer has a fixed array of switches and works in terms of switches being on or off. The human brain has synapses which act as switches, but these can vary in connection strength: they can be more or less on.

Moreover, the actually set of 'switches' is not fixed: connections between cells can be added to or removed, and indeed a key aspect of development in young humans is an extensive pruning of most of the initial connections established, to provide a more selective network. This provides the potential for a much more flexible, and responsive, processing apparatus than is possible with an electronic computer – where the stability of the set of connections in the processor is rather important to its normal functioning. This immediately suggests that humans and computers are going to have rather different properties as processing systems and so also have rather different strengths and weaknesses.

Related to this is the type of processing undertaken in a system with the type of structure and inherent plasticity of a synaptic network. The input to one node, one neuron, can be from a range of different other nodes, and it can in turn provide output to a range of other nodes – each with changeable connection strengths. Moreover, output can through a chain of connections influence input: that is, there is potential for feedback in the system.

Systems of this type have potential for undergoing changes that can be considered as learning. Artificial networks of this kind have been 'trained' to undertake processing tasks such as, for example, distinguishing the sonar patterns obtained from shoals of fish and submarines: a kind of task that because of its complexity – due to variations in size, shape and distance of target; water conditions and other objects influencing echoes, etc. – is very difficult to achieve with binary electronic computers that have to be programmed in terms of a series of if/then decision-making steps.

Whereas programming an electronic computer for such a task requires an extensive analysis of the task and subsequent highly complex programme, synaptic networks are 'trained' by changing connections strength patterns in an iterative manner: feedback is used to see which changes produce more effective outcomes, and which is less effective, and over time the system is tuned to its function. Now as human cognition is more like the artificial synoptic networks than binary electronic computers, it seems that their processing is better understood by analogy with such networks. That is, rather than considering processing in the brain to be *as if* someone has written a compiler to translate sensory input signals into a machine code, it may be more appropriate to think of it *as if* somebody has finely tuned output patterns from available input, by considering the feedback to an extensive set of trials. It should be noted that the actual system properties of a particular brain depend upon both features which are in effect genetically programmed by the 'feedback' effects of natural selection acting over many generations (see below) and the individual's experiences, responses to those experiences and subsequent experience of effects of their responses.

The Ghost in the Machine: Who Tunes Our Processing Networks?

However, a major difference between the artificial synaptic network and a human brain is the nature of a trainer. When an artificial network is trained to distinguish fish from submarines or perhaps appendicitis from intestinal wind in a medical diagnostic system, the external trainer makes external judgements about the accuracy of outputs and uses these to decide how to proceed to tune the circuit.

But just as there is no programmer writing code for human brains, the newborn infant has no external trainer to suggest which outputs are accurate representations of input from the external world. Rather, learning has to involve modifying synaptic connection strengths depending upon whether the output of attempts to act on the world are considered more or less effective in meeting internal drives. The hit-and-miss nature of this business suggests that a great many trials might be needed before any human cognitive system could be well enough 'tuned' to offer an effective model of the outside world.

However, there is a mechanism for the learning of one generation to allow the next to have something of a 'head start' in this process. The transfer of genetic information to offspring has allowed natural selection to operate over a great many generations so that each new individual is not starting ab initio, expected to make sense of the world with a random network of neutrons that has to be moulded into a tuned processing system ex nihilo, but enters the world with both initial apparatus and inbuilt tendencies to direct development, which are the results of testing over millions of years. Certainly within the chordates, the initial state of any individual's cognitive system is highly biased. In humans this is especially so, for as we have seen there are innate tendencies to acquire verbal language, for example.

That is an especially helpful adaptation, because it means that from quite early in the young person's development, the tuning of the cognitive systems can be *supported* by external trainers (Vygotsky, 1978), who supplement the initial drives to make sense of an act in the world by providing extensive additional feedback (e.g. no that is not a doggy, that is a cat). Whilst this feedback itself needs to be interpreted within the system (see Chap. 4), it offers additional sources of information about how humans have found it helpful to understand the world.

Emergent Systems

This reiterates a point made near the start of this part of the book (in Chap. 3), about the emergence of properties. If we accept the consensual scientific model of evolution by natural selection, then the way in which human brains process information about the world is simply the result of selection pressures acting on organisms that cope differentially in their environments and which are able to pass on genetic material causing their offspring to tend to be like them.

The human sensory interface that translates sensory information into electrical patterns in the cognitive system is simply an outcomes of that process, and the 'coding' is simply what has emerged as a solution that worked. That is, it has in the past tended to allow individuals to leave offspring. It is a system that 'fits' with the need to be able to make sense of, and act on, the environment. Similarly, other aspects of cognition have presumably emerged in the same way: the nature of our percepts, the development of consciousness, the limitations of working memory, the nature of our concepts and conceptual systems, our use of logic and our creative abilities, our ability to reflect on our own cognition and so forth. If all of this relies on the self-organisational properties of synaptic networks that can be tuned through feedback, then there is no established machine code that acts as a natural language of thought that we would recognise as akin to human codes or languages: rather we have evolved cognition that offers survival value, based on coding templates that are largely our common genetic inheritance as humans, but which presumably themselves show individual variation. Unlike electronic computers that are often cloned in the millions, we each have both a somewhat unique processor and a somewhat unique 'operating system'.

Key Terms from the Mental Register

As noted in the part introduction, this part contains five chapters exploring what we understand by, and how we might investigate, such matters as learners' ideas, learners' thinking and learners' understanding. In this part I have attempted to explore what these terms might be considered to mean when used as part of a way of modelling the learner's cognition.

As suggested earlier in the book, during our childhood, we all develop an implicit 'theory of mind' that supports everyday dialogue in terms of a more or less shared 'folk psychology' supported by an informal 'mental register' of terms. So in everyday dialogue, we may commonly use a term like 'thinking' to refer to both processes and the outcomes of those processes, and it is common to talk about memory as though it is a place within the mind where we can store experiences or information that we may wish to access later. This works fine in the context of normal social dialogue but can become problematic when we use the same terms in the context of formal research and scholarship. As I suggested in the introductory chapter, too often in research in science education, the components of the mental register are adopted without any formal definition, as though they are well-defined technical terms.

Within any research programme, there will be widely shared technical terms that have been established and which do not need to be spelt out in detail each time they are used in a study. In the research programme into learning in science, there are such technical notions (such as alternative conceptions and phenomenological primitives; see Chap. 11), but commonly researchers have also borrowed terms from the mental register – thinking, understanding, remembering, etc. – as though these are also accepted technical terms. The need for using either these notions or

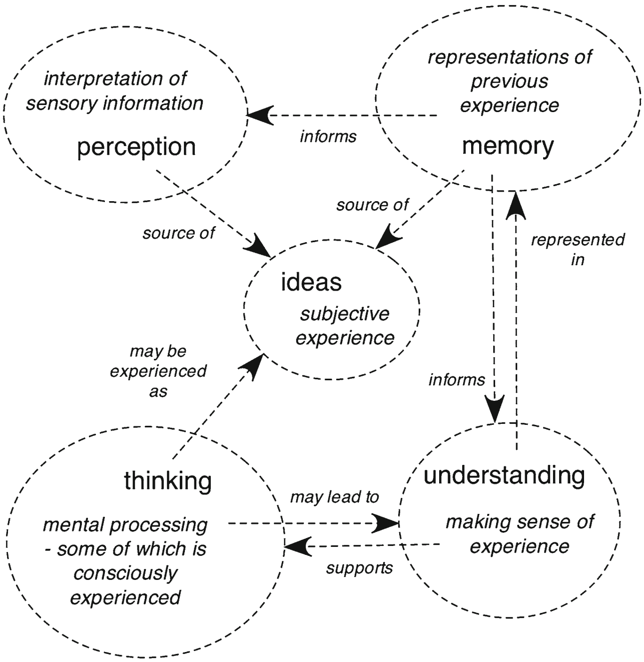

Fig. 7.6 Mental processes – a model relating some key terms used in research into learning in science

alternatives that cover the same set of phenomena in the research programme is clear, but the close familiarity with and taken-for-granted nature of the use of the mental register has led to such terms being used *as if* technical terms, without usually being operationalised in any explicit way.

In this part of the book, I have set out a way of thinking about key notions from the mental register, informed by well-accepted ideas from the cognitive sciences, that can act as a basis for reformulating these notions as constructs suitable for discussing in research. That is, I have been building up a model for how these terms can be understood to relate and to refer to observables in research. So assuming that mind is an emergent property of the central nervous system – indeed of largely the cortical areas of the brain – and is for many purposes best understood in functional terms as a system for processing information (but which leads to conscious experience), I have suggested how we could best understand notions such as thinking, understanding and remembering. Figure 7.6 summarises the meanings that have been established for five of the key terms: perception, memory, ideas, understanding and thinking.