Chapter 12: Problem solving and expertise

This chapter is concerned primarily with problem solving. One line of research has had as its focus the identification of the processes used to solve problems that do not require specialised knowledge for their solution. Another line of research has concentrated on the role of learning in problem solving, with a particular emphasis on the knowledge and skills possessed by experts but not by novices.

We often find ourselves in situations where we need to solve a problem. We will consider three examples here:

- First, you have an urgent meeting in another city and so must get there as soon as possible. However, the trains generally run late or are cancelled, your car is old and unreliable and the buses are slow.
- Second, you are struggling to work out the correct sequence of operations to make your new computer do what you want to do. You try to remember what you needed to do with your previous computer.
- Third, you are an expert chess player in the middle of a competitive match against a strong opponent. The time-clock is ticking away, and you have to decide on your move in a complicated position.

There are many types of thinking:

- **Problem solving**: cognitive activity that involves moving from the recognition that there is a problem through a series of steps to the solution. Most other forms of thinking involve some problem solving.
- **Decision making**: selecting one out of a number of presented options or possibilities, with the decision having personal consequences.
- **Judgement**: a component of decision making that involves calculating the likelihood of various possible events; the emphasis is on accuracy.
- **Deductive reasoning**: deciding what conclusions follow necessarily, provided that various statements are assumed to be true; a form of reasoning that is supposed to be based on logic.
- **Inductive reasoning**: deciding whether certain statements or reasoning hypotheses are true on the basis of the available information. It is used by scientists and detectives but is not guaranteed to produce valid conclusions.
- **Informal reasoning**: evaluating the strength of arguments by taking reasoning account of one’s knowledge and experience.

**What’s in this chapter?**

- **Problem solving: introduction**

There are three major aspects to problem solving:

- It is purposeful (i.e., goal-directed).
- It involves controlled processes and is not totally reliant on “automatic” processes.
- A problem exists when someone lacks the relevant knowledge to produce an immediate solution. Thus, a problem for most people (e.g., a mathematical calculation) may not be so for a professional mathematician.

There are two types of problems:

- well-defined problems;
- ill-defined problems.

Most psychological research focuses on well-defined problems, whereas most everyday problems are ill-defined (Goel, 2010). We must also distinguish between knowledge-rich and knowledge-lean problems. Knowledge-rich problems (e.g., chess problems) can only be solved by those having much relevant specific knowledge. In contrast, knowledge-lean problems do not require such knowledge.

**INTERACTIVE EXERCISE**: Well-defined problems
**Gestalt approach: insight and role of experience**

Gestaltists distinguished between reproductive and productive thinking.

- **Reproductive thinking** involves the systematic reuse of previous experiences.
- **Productive thinking** involves a novel restructuring of the problem and is more complex.

Insight involves a sudden restructuring of a problem and is sometimes accompanied by the “ah-ha experience” (Kounios & Beeman, 2014). Metcalfe and Wiebe (1987) recorded participants’ feelings of “warmth” (closeness to solution) during insight and non-insight problems. Warmth increased progressively during non-insight problems (as expected if they involve a sequence of processes). With insight problems, in contrast, the warmth ratings remained at the same low level until suddenly increasing dramatically just before the solution was reached.

**Differences in brain activity between insight and non-insight trials centred in the right anterior superior temporal gyrus (Bowden et al., 2005). Several studies found insight was associated with activation of the prefrontal cortex (involved in higher cognitive processes) (Kounios & Beeman, 2014). Ellis et al. (2011) recorded eye movements during the anagram task. On most trials, participants reported they had suddenly solved the anagram (insight trials). However, the eye-movement data told a different story. During each insight trial, participants spent a gradually decreasing percentage of their time fixating the distractor consonant.**

**Thomas and Lleras (2009) used the pendulum problem with occasional exercise breaks in which participants swung or stretched their arms. Those moving their arms in a solution-relevant way (i.e., swinging) were more likely to solve the problem than those stretching their arms, although they were unaware of the relationship between their arm movements and the task. Thus, hints help with insight problems.**

Wallas (1926) argued for the importance of **incubation**, in which a problem is put aside for some time. He claimed the subconscious mind continues to work towards a solution during incubation and so incubation facilitates problem solution. Sio and Ormerod (2009) reported three findings about incubation:

- Incubation effects (generally fairly small) were reported in 73% of the studies.
- Incubation effects were stronger with creative problems having multiple solutions than linguistic and verbal problems having a single solution. Incubation often widens the search for knowledge, which may be more useful with multiple-solution problems.
- The effects were larger when there was a fairly long preparation time prior to incubation. This may have occurred because an impasse or block in thinking is more likely to develop when preparation time is long.

Sio et al. (2013) found, using the Remote Associates Test, that sleep enhanced performance on difficult problems but not on easy ones. Penaloza and Calvillo (2012) obtained evidence that forgetting misleading information is important.

Ohlsson (1992) argued that we often encounter a block or impasse when solving a problem because we have represented it wrongly. Ohlsson’s (1992) representational change theory suggests we need to change the problem representation for insight to occur. This can happen in three ways:

- **Constraint relaxation**: inhibitions on what is regarded as permissible are removed.
- **Re-encoding**: some aspect of the problem representation is reinterpreted.
• **Elaboration:** new problem information is added to the representation.

The importance of constraint relaxation was shown by Knoblich et al. (1999). Reverberi et al. (2005) argued that individuals’ processing constraints when on insight problems involve the lateral prefrontal cortex. Decreased excitability of the left lateral prefrontal cortex probably reduced inhibitions about constraint relaxation. Increased excitability on the right side may have enhanced insight processes (Chi & Snyder, 2011). Hints before or after an impasse improved performance less than those given at the point of impasse (Moss et al., 2011). Ölinger et al. (2014) found insight needed to be followed by an efficient search process for the problem to be solved.

While this theory is a useful addition to Gestaltist principles, it is unclear why or when representations will change. Individual differences are ignored in this model. Constraint relaxation is not always needed to change representations.

*Functional fixedness* occurs when we mistakenly assume that any given object has only a limited number of uses based on previous knowledge. Duncker (1945) demonstrated that participants fixate on the single use of objects. Ye et al. (2009) demonstrated that participants’ previous use of an object influenced their next use. Challoner (2009) suggested two things are needed to solve insight problems:

- Notice an infrequently noticed or new feature.
- Form a solution based on that obscure feature.

Chrysikou et al. (2013) argued that high levels of cognitive control can produce functional fixedness.

There is another way past experience can impair problem solving: *mental set*. Mental set involves continuing to use a previously successful problem-solving strategy even when it is inappropriate or sub-optimal. People tend to use a longer solution based on a familiar strategy (Bilalić et al., 2008a). This is due to participants focusing only on the familiar solution.

Problem solving is goal directed and involves cognitive rather than automatic processes. The Gestalt psychologists argued that problems often require insight, and past experience sometimes disrupts current problem solving. Ohlsson’s representational change theory is a neo-Gestalt theory emphasising the importance of changing representations through elaboration, constraint relaxation and re-encoding, for insight to occur.

• **Problem-solving strategies**

Newell and Simon (1972; see Eysenck & Keane, 2010, p. 470) argued that it is possible to produce systematic computer simulations of human problem solving. They suggested the *General Problem Solver* with the following assumptions:

- Information processing is serial.
- People possess limited short-term memory capacity.
- Relevant information from long-term memory can be retrieved.

Problems are represented as a *problem space*, which consists of the initial state of the problem, the goal state, all of the possible mental operators and all intermediate states of the problem. The Tower of Hanoi problem has been used to illustrate the theory.

**WEBLINK:** [Tower of Hanoi](https://en.wikipedia.org/wiki/Tower_of_Hanoi)

The complexity of most problems means that we rely heavily on *heuristics* as opposed to *algorithms*. Important heuristic methods are *means–ends analysis* and *hill climbing*.

- Means–ends analysis involves:
  - noting differences between current and goal states;
• forming a subgoal that will reduce this difference;
• selecting a mental operator that will permit attainment of the subgoal.

Hill climbing involves changing the present state within the problem into one closer to the goal solution. It is a simpler heuristic than means–ends analysis.

Newell and Simon applied the General Problem Solver to 11 different problems (including the Tower of Hanoi), and although it solved all the problems it did not always do so in the same way as people.

MacGregor et al. (2001) argued that people use the heuristic of progress monitoring in which the rate of progress towards a goal is assessed, and criterion failure leads to strategy change. MacGregor et al. (2001) found evidence for progress monitoring in a nine-dot problem.

Planning is also critically involved in problem solving and involves the prefrontal cortex. Goel and Grafman (1995) found patients with prefrontal damage performed worse than healthy controls on the Tower of Hanoi task. Goel et al. (2013) used a real-world travel planning task in which participants had to organise a trip to Italy for an American couple. Patients with right prefrontal damage had impaired planning in part because they made premature commitments to various decisions.

Planning is only part of a sequence of processing stages including plan production and plan execution. With complex tasks, only some moves are typically planned, so executing the initial plan is followed by generating a further plan and then its execution. Evidence supporting the distinction between plan production and plan execution was reported by Crescentini et al. (2012). Nitschke et al. (2012) argued that Tower of London problems require participants to engage in problem representation followed by planning.

There is much evidence for individual differences in planning (Koppenol-Gonzalez et al., 2010). Evidence suggesting important problem-solving processes occur below the level of conscious awareness was reported by Paynter et al. (2010). Patsenko and Altmann (2010) provided some of the strongest evidence that most problem solvers may engage in little planning.

Many theorists have proposed dual-process theories to account for the strategies used by individuals performing cognitive tasks such as judgement and reasoning (Evans, 2008). Most dual-process theorists argue that many people are cognitive misers. A cognitive miser is someone who is typically economical with his/her time and effort on tasks requiring thinking. The Cognitive Reflection Test provides evidence of the extent to which people are cognitive misers (Frederick, 2005). Low scorers on the Cognitive Reflection Test perform relatively poorly on a wide range of judgement, reasoning tasks and measures of intelligence (Toplak et al., 2011).

WEBLINK: Cognitive reflection test

Newell and Simon’s General Problem Solver is a computer program based on the assumptions that processing is serial and that people have limited short-term memory capacity. According to the theory, problem solvers make extensive use of heuristics. The General Problem Solver has better memory than (but inferior planning ability to) humans.

• Analogical problem solving

Much research on positive and negative transfer has involved analogical problem solving, in which the solver uses similarities between the current problem and one or more problems in the past. When people do not have knowledge directly relevant to a problem, they apply knowledge indirectly by analogy to the problem. Chen (2002) stated that there are three main types of similarity between problems:

• Superficial similarity: Solution-irrelevant details (e.g., specific objects) are common to the two problems.
- **Structural similarity**: Causal relations among some of the main components are shared by both problems.

- **Procedural similarity**: Procedures for turning the solution principle into concrete operations are common to both problems.

Analogical reasoning has been found to correlate highly with intelligence (Spearman, 1927), suggesting the involvement of higher-level cognitive processes such as the central executive (Morrison, 2005).

**WEBLINK**: An overview of analogy-making

Gick and Holyoak (1980) studied Duncker’s radiation problem. Only 10% of participants given the problem on its own solved it. When a story relevant to the problem was provided, 40% of participants solved the radiation problem. This rose to 80% when participants were told that the second story was relevant. Keane (1987) varied the semantic similarities between the problem and the story; 88% of those given a close analogy spontaneously used it for the problem, compared to 12% for the remote analogy. Dunbar and Blanchette (2001) found evidence that the types of analogies people use depend on their current goals. Kurtz and Loewenstein (2007) argued that it would be easier to grasp the underlying structure of a problem if it was compared directly to another problem with the same structure.

Four-term analogy problems involve three sequential processing stages:

- **encoding** of the first pair of words based on the relationship between them;
- **mapping** (a connection is formed between the first words of each pair and an inference drawn as to the fourth word);
- **response** (decision concerning the correctness of the fourth word).

Knowlton et al. (2012) argued that it has to involve serial processing (one process at a time) because of the processing demands involved. Krawczyk (2012) summarised neuroimaging and patient research on the brain areas involved in analogical reasoning. Occipital and parietal regions are used for visual and spatial processing, followed by extensive involvement of the prefrontal cortex. Krawczyk et al. (2008) argued that successful analogical problem solving often requires executive processes inhibiting responding to relevant distractors. Cho et al. (2010) identified more precisely the prefrontal regions involved in inhibitory control. Activity in the inferior frontal gyrus increased when the amount of interfering information increased and so there was greater need for inhibitory control. Schmidt et al. (2012) argued that processes (and brain areas) involved in analogical processing depend on the precise nature of the analogy.

**INTERACTIVE EXERCISE**: Brain areas involved in reasoning

The working memory system is involved in analogical problem solving (Morrison et al., 2001). Cho et al. (2007) obtained further support for the involvement of working memory in analogical problems. Analogical performance was especially poor when participants faced the combination of high problem complexity and interference resolution, because this overloaded the central executive.

Analogical reasoning performance correlates about +0.7 with intelligence (Spearman, 1927). Ackerman et al. (2005) found in a meta-analysis that the overall correlation between those two measures was +0.50. Chuderski and Necka (2012) obtained measures of attentional capacity and attentional control. Attentional capacity correlated highly with performance on the Raven’s Matrices.

Transfer of training depends on content (what is transferred from one task to another) and on context (when and where knowledge is transferred from and to). Far transfer is of great importance for education. It has been obtained in several studies, and can be facilitated by the development of metacognitive skills. Transfer in analogical problem solving depends on three kinds of similarity: superficial, structural and procedural. The
central executive system is heavily involved in analogical problem solving. Inhibitory processes are needed to prevent interference from distractors.

- **Expertise**

People sometimes spend several years acquiring knowledge and skills – the end point is *expertise*:
- The processes involved in achieving expertise are known as *skill acquisition*.
- An important and well-studied area is chess-playing expertise.

- **Chess-playing expertise**

Chase and Simon (1973) estimated that it takes at least ten years of intensive practice to become an international chess master. De Groot (1965) tested the notion that expert chess players have detailed information about chess positions stored, which allows them to relate the current game to past games. Chess masters were better at recognising and encoding the various configurations of chess pieces than less expert players.

**WEBLINK:** An article on Deeper Blue

Gobet and Waters (2003) developed *template theory*. According to template theory, chunks that are used frequently develop into more complex data structures known as *templates*:
- These are schematic structures consisting of a core and slots.
- Templates typically store information relating to ten pieces or more.
- Templates are more flexible and adaptable than chunks.

Template theory makes the following predictions:
1. The chunks are larger and fewer in number than assumed by chunking theory.
   - Gobet and Clarkson (2004) provided strong support for the prediction that expert players have larger-sized templates, and that the number of templates does not vary as a function of playing strength.
2. Good chess players have superior template-based knowledge of chess which can be accessed rapidly.
   - Charness et al. (2001) showed that expert players assess chess positions very rapidly.
   - Burns (2004) found that performance in blitz chess correlated highly with performance in normal chess, indicating the use of template-based knowledge in both conditions.
   - Moxley et al. (2012) found slow, strategy-based processes are very important in determining chess performance.
3. Expert chess players store the precise board locations of pieces.
   - McGregor and Howes (2002) discussed an important limitation that most tests ask players to memorise positions when evaluation is more realistic. There is evidence that players evaluating positions remember relationships between pieces better than locations.
4. Expert chess players have better recall of random chess positions.
   - Gobet and Simon (1996) carried out a meta-analysis and found only a small effect of skill on random board positions.

**CASE STUDY:** Recording the eye movements of expert chess players

There is evidence that experts store a few large templates rather than many chunks. Template-based knowledge may explain how it is that expert chess players can identify key pieces in a board position in under one second, and how outstanding players can play effectively under time pressure. Limitations of template theory are:
- Slow search processes are more important than assumed, as performance of the best experts still suffers with time pressure, suggesting that rapid access to templates is important.
- Skilled players can use strategies that go beyond knowledge.
- The precise information stored in long-term memory remains controversial.
Expertise is typically assessed by using knowledge-rich problems. Computers consider a much greater number of possibilities before making a move than do outstanding chess players. There is evidence that expert chess players store a few large templates containing knowledge of chess positions rather than many smaller chunks. These templates allow expert players to identify good moves rapidly and to remember even random chess positions better than non-experts. The precise information contained in templates remains unclear, and template theory may not fully account for the adaptive expertise shown by outstanding players.

- **Medical expertise**

Medical expertise describes the ability of medical experts to make rapid and accurate diagnoses. Medical decision making is often a life-or-death matter, and is important to understand. It is assumed medical experts differ from novices in that they use implicit reasoning rather than explicit reasoning.

Krupinski et al. (2006) found greater expertise was associated with more information being extracted from the initial fixation. Experts relied on global impression, while novices made more use of focal search. Kundel et al. (2007) found experts took less time to fixate a cancer, and this was predictive of high performance. Early evidence that medical experts can detect abnormalities very rapidly was reported by Kundel and Nodine (1975).

Gegenfurtner et al. (2011) identified several differences between experts and non-experts that were common across domains:
- shorter fixations;
- faster first fixations on task-relevant information;
- more fixations on task-relevant information;
- fewer fixations on task-irrelevant areas;
- longer saccades (rapid eye movements).

According to the information-reduction hypothesis (Haider & Frensch, 1999), the development of expertise is associated with an increasingly efficient and selective allocation of attention. According to the holistic model (Kundel et al., 2007), experts can extract information from a wider area than non-experts with each fixation.

Melo et al. (2012) suggested medical experts engage in rapid pattern recognition. Analytic thinking enhanced the diagnostic performance of experts with complex cases but not simple ones. In contrast, non-experts derived no benefit from engaging in analytic thinking (Mamede et al., 2010).

There is convincing evidence that the processes used by medical experts and non-experts differ qualitatively. Medical experts rely more on fast, automatic processes in diagnosis, but their reliance on gist-based processes can sometimes impair performance. Limitations of research on medical expertise are:
- Most studies have compared experts and non-experts. This is uninformative about specific learning processes involved in the development of expertise.
- There is a danger of underestimating the value of analytic processing.
- More research is needed to compare the various theories.

Medical and chess expertise share similarities:
- Several years of intensive training are needed.
- Training leads to acquisition of huge amounts of stored knowledge.
- Experts are better able to make use of rapid automatic processes.
- Experts can make flexible use of analytic strategies when required.

There are also differences between chess and medical expertise:
- The form in which knowledge is stored differs.
- The way in which chess and medical experts use their expertise is different.
There is evidence that the processes used by medical experts in diagnosis differ qualitatively from those used by non-experts. Medical experts rely on fast, automatic processes in diagnosis, but their reliance on gist-based processes can sometimes impair performance.

- **Brain plasticity**

We know the development of expertise involves acquiring huge amounts of knowledge and specialised cognitive processes and potentially changes in the brain – plasticity (Herholz & Zatorre, 2012).

Experienced London cab drivers have a greater volume of grey matter in the posterior hippocampus than novice drivers or other control groups, and older full-time cab drivers have greater grey matter volume in this area than those of the same age who have retired (Woollett et al., 2009). Individuals learning to juggle showed a 5% increase in grey and white matter in the visual motion area over a 6-week training period, and this increase was mostly still present at follow-up (Scholz et al., 2009). Several studies have assessed the effects of musical training on changes in brain structure and function (Herholz and Zatorre, 2012; Zatorre, 2013). Such changes (e.g., greater volume or thickness of auditory cortex) are present at all ages. Numerous studies have shown predictable differences in brain structure between individuals with varying levels of training in a given domain (Zatorre, 2013).

- **Deliberate practice**

Ericsson and Towne (2010) argued that expertise can be developed through deliberate practice. Deliberate practice has four aspects:

  1. The task is at an appropriate level of difficulty.
  2. The learner is given informative feedback about performance.
  3. The learner has chances to repeat the task.
  4. The learner has the opportunity to correct his/her errors.

Ericsson and Kintsch (1995) proposed the notion of long-term working memory: experts store relevant information in long-term memory that can be readily accessed through retrieval cues in working memory.

**RESEARCH ACTIVITY 1**: Skill acquisition and the Power Law

**RESEARCH ACTIVITY 2**: Skill acquisition: cultural differences in learning to count

There is evidence that experts make use of long-term working memory to enhance their ability to remember information. Ericsson and Chase (1982) studied SF, who increased his digit-span from 7 digits to 80 digits after two years by making use of long-term working memory. Guida et al. (2012, 2013) reviewed neuroimaging findings in studies of experts performing tasks involving use of working memory. The experts showed decreased activation in prefrontal and parietal areas as chunks were created and retrieved, and increased activation in medial temporal regions strongly associated with long-term memory as knowledge structures were created and retrieved. This pattern of findings differed from that of non-experts and suggests only experts used long-term working memory extensively. The performance level of experts is highly correlated with the amount of deliberate practice they have had (Campitelli & Gobet, 2011). Tuffiash et al. (2007) found elite Scrabble players differed from average players on deliberate practice activities, but not on other forms of practice.

However, there is stronger evidence for the importance of intelligence in development of very broad expertise. Hambrick et al. (2014). On average, variations in deliberate practice accounted for only 34% of chess-playing performance and 29.9% of music performance. Correlations between amount of practice and skill level probably depend on two factors:

- Deliberate practice enhances skill level.
- Early success leads to greater subsequent practice.
Campitelli and Gobet (2011) identified three predictions from distributed practice theory:

- All individuals who engage in massive distributed practice should achieve very high skill levels.
- The variability across individuals in the number of hours required to achieve high expertise should be relatively small.
- Everyone’s skill level should benefit comparably from any given amount of distributed practice.

Gottfredson (1997) found that the correlation between intelligence and work performance was +0.23 for low-complexity jobs but rose to +0.58 for high-complexity jobs. Meinz and Hambrick (2010) studied factors influencing piano-playing skill. Sight-reading performance correlated +0.67 with total amount of deliberate practice.

There is strong support for the view that memory in a domain of expertise can be developed by the use of long-term working memory. Evidence indicates that deliberate practice is necessary for the achievement of expertise. However, there are the following limitations to research in this area:

- It has proved hard to assess deliberate practice with precision.
- While level of expertise is strongly correlated with amount of distributed practice it does not imply causality.
- The evidence suggests deliberate practice is necessary (but not sufficient) to produce high levels of expertise.
- The notion that innate talent is unimportant is unconvincing.
- Individual differences in talent as assessed by intelligence tests are important.

According to Ericsson, the development of expertise depends on deliberate practice involving informative feedback and the opportunity to correct errors. Deliberate practice is necessary for the development of expertise, but it is rarely sufficient. Individual differences in innate ability are also important, and it may be mainly individuals of high innate ability who are willing to devote hundreds or thousands of hours to deliberate practice.

Additional references