Spontaneous Analogising in Engineering Design: A Comparative Analysis of Experts and Novices

Linden J. Ball
Thomas C. Ormerod
Nicola J. Morley

Analogical reasoning is claimed to play a central role in creative cognition and the development of expertise. To date, however, few studies have explored the nature and prevalence of spontaneous analogising in design contexts. In the present paper we report an experimental comparison of analogy use by expert and novice engineering designers who were presented with a brief to design a conceptual solution for an automated rent-a-car facility. Concurrent think-aloud protocols were elicited and analysed to derive measures of the rate of participants' schema-driven analogising (defined as the recognition-primed application of *abstract* experiential knowledge that could afford a design solution to a familiar problem type), and participants' case-driven analogising (defined as the invocation of a *concrete* prior design problem whose solution elements could be explicitly mapped onto the current problem). Results supported our central prediction that expert designers would demonstrate more schema-driven than case-driven analogising, whilst novices would show the reverse pattern of analogy use. We discuss the implications of these results for theories of design cognition and expert design practice.

Analogical reasoning entails the use of 'source' information from a previous problem-solving episode as a means to facilitate attempts at solving a current, 'target' problem. Theorists have traditionally viewed analogical reasoning as a core element of intelligent thought (Raven 1938, Sternberg 1977), and recent evidence suggests that analogising may play a particularly central role in creative problem solving (Holyoak and Thagard 1995) and domain-based skill acquisition (Anderson 1989, Schank 1999). In spite of the vital function that is claimed for analogical reasoning in innovative thinking and the development of expertise, little existing research appears to have given serious attention to the nature, quantity and function of analogising in design contexts. This is, perhaps, more than a little surprising, as design tasks are not only ubiquitous in many professional work endeavours (Goel and Pirolli 1992) but they are also commonly viewed as prototypical cases of complex and ill-defined problems of the kind whose solution should benefit from the application of prior domain-specific knowledge (cf. Ball et al. 1997, Simon 1981).

Given the limited amount of existing work on analogical processes in design, the present research aimed to tackle head-on some of the key issues relating to designers' use of prior knowledge, and the links between analogising and expertise. Our main focus was to address three pivotal and interrelated questions: (1) What evidence is there that designers are able *spontaneously* to invoke and apply prior analogues when tackling their current design problems or sub-problems?; (2) What comparisons can be drawn between the kinds of analogising evidenced by expert design practitioners and the kinds of analogising arising in the problem-solving efforts of novice designers who possess only a few years of practical design experience?; and (3) What types of available cues drive a designer's search for, and application of, analogous source problems and solutions?

In order to address these issues in the present paper we initially undertake a review of the psychological literature on analogical problem solving with a view to identifying key observations concerning the use of analogical reasoning as a fundamental problem-solving procedure in domain experts and novices. A critical aspect of this review is to assess how distinct *forms* of analogical reasoning may differentially dominate expert and novice performance in domain-based problem-solving tasks, including design tasks. In relation to experts, for example, we develop the proposal that performance will be characterised by more *schema-driven analogising* (applied to highly familiar domain problems) and less *case-driven analogising* (applied to less familiar domain problems). As far as novices are concerned, however, we predict the reverse pattern of observations, as novices simply will not possess much in the way of schematised domain knowledge derived from extensive prior experience.

We discuss the notions of schema-driven and case-driven analogising in more detail below. Suffice it to say for now that we use the term 'schema' in its conventional sense (e.g., Chi, Feltovich and Glaser 1981) to denote an abstract knowledge structure, developed through extensive domain-based experience, that can function automatically to recognise a class of problems and to afford an appropriate solution procedure. As such, what we describe as 'schema-driven analogising' entails the rapid, automatic, and implicit identification and application of *abstract* experiential knowledge that is relevant to the task at hand. In contrast, what we term 'case-driven analogising' aims to capture the idea that analogising may sometimes involve the strategic identification of a *concrete* prior problem whose solution can be mapped systematically onto the current problem. Our concept of case-driven analogising has direct counterparts in the literature on so-called 'case-based reasoning' (e.g., Kolodner 1993), and is clearly oppositional to schema-driven analogising in that it entails relatively slow, effortful and explicit analogical-reasoning processes involving contentful rather abstracted knowledge.

Our literature review focuses primarily on laboratory-based experiments of analogical problem solving, as these have been the mainstay of existing research in this area. Some recent real-world studies of analogical reasoning have, however, been conducted, and typically generalise laboratory-derived findings to professional problem-solving contexts (Bearman, Ball and Ormerod 2002, Blanchette and Dunbar 2000, Thompson, Gentner and Loewenstein 2000). In addition, it should be noted that most of the research that we discuss is, of necessity, non-design focused, although where we are aware of pertinent design-oriented analyses of analogical reasoning we introduce this material into the review. Subsequent to our examination of the literature we report on a small-scale study that we have recently conducted that was directed at eliciting a comparative understanding of expert versus novice analogising in industrial design. Our experts were company-based engineers with extensive commercial design experience. Our novices were masters-level students who had been involved in a design and development projects as part of their undergraduate and graduate work, including periods of company-based placement.

1. Empirical studies of analogical reasoning in problem solving

1.1. The spontaneous use of analogies

In spite of the postulated importance of analogical reasoning for intelligent human behaviour, studies conducted over the past twenty years or so have suggested that the *spontaneous* consideration of analogies in problem solving may be rather limited in its occurrence. For example, pioneering experiments by Gick and Holyoak (1980, 1983) demonstrated that providing participants with a source analogue prior to them tackling a superficially different but conceptually similar target problem gave little or no gain over baseline solution rates where no analogue had previously been presented. It was only in those conditions where explicit hints were provided about the relevance of the source information to the target problem that good levels of facilitated target performance arose (cf. Anoli et al. 2001). Casakin and Goldschmidt (1999) have similarly demonstrated how, in the design domain, both novices and experts can make effective use of visual analogies for current design work when explicitly directed to do so, but are more limited in their spontaneous use of such visual analogies. Other studies have clarified that the transfer of an analogous solution in the absence of directive hints is also not improved by factors such as: (1) giving participants a static diagrammatic representation of the underlying solution-structure associated with the base problem (Gick and Holyoak 1983, Pedone, Hummel and Holyoak 2001); (2) providing problem solvers with an abstract verbal statement summarising the underlying conceptual nature of the base problem and solution (Gick and Holyoak 1983); or (3) re-presenting the source information to the participant whilst they are actually processing the target (Anoli et al. 2001, Gick and Holyoak 1980). Taken together, this evidence has been viewed by some theorists as support for the contention that whilst people are very good at utilising prior problem and solution information when they are directed to do so, they may be rather poor at detecting such analogous information under unprompted conditions.

Some studies, however, have produced more positive evidence for the spontaneous use of analogies by problem solvers. For example, Holyoak and Koh (1987) and Keane (1987) have demonstrated that people are readily able to notice and make use of prior analogues when there are high levels of *surface similarity* in the information content of the source and target problems. This latter situation arguably maps more closely on to much real-world problem solving, where 'within-domain' analogies involving close variants of a target problem are likely to be available. For example, if an industrial designer is tackling an information-display problem, say a design for a gas-meter read-out, then they may well bring to mind previous design experience relating to other displays that they have worked on in the past—perhaps relating to an electricity meter, a fuel gauge or a seismic indicator. Indeed, Visser (1996) presents compelling evidence for the spontaneous application of within-domain analogies by an individual expert designer tackling an unfamiliar design problem (see Cross, Christiaans and Dorst 1996, for a full report of this designer's activity, which was analysed as part of the Delft Protocols Workshop on design). At a theoretical level, Sweller (1980) has argued that much of the time there is a strong correlation between the *surface features* of problems and their underlying, *abstract solution structures*. Therefore, relying on surface features to access what might be a relevant source problem may often be a valuable heuristic (Blessing and Ross 1996), and one that the human cognitive system may well have evolved to operate. As a heuristic, however, it is likely to be far from foolproof, and may, on occasions, lead to attempts to map between source and target problems that, whilst appearing to be superficially similar at a surface level, in fact have no underlying conceptual association in terms of their solution structures (e.g., see Novick, 1988, for relevant evidence).

1.2. Analogical reasoning and expertise

Apart from the role of surface similarity in driving spontaneous analogical reasoning, other research has provided evidence for unprompted analogising when *multiple* analogous sources are presented prior to the target problem, even when these sources share no surface similarities to the target (Catrambone and Holyoak 1989, Gick and Holyoak 1983). This line of research is particularly interesting as it suggests that the primary mechanism underpinning the development of domain-based expertise may well be analogical reasoning. The essential claim of theorists taking this position (e.g., Anderson 1989, Gick and Holyoak 1983, Blessing and Ross 1996) is that repeated exposure to within-domain problems (or what Dunbar and Blanchette 2001 refer to as 'local' analogies) serves to promote the induction of generalised *knowledge schemas*. As we noted previously, such schemas embody an abstract *conceptual* understanding of the underlying nature of problems, and serve to enable the recognition of problem 'types'; they also embody a *procedural* understanding of how best to solve problems of that particular type.

Attempts at explaining fully the processes of schema acquisition and schema application have fuelled much of the psychological literature on expert-novice differences over the past few decades. Central within this literature has been the view that the correct perception of a problem by an expert will automatically cue access to an appropriate schema and the immediate invocation of a straightforward—even stereotypical—solution method (Chi et al. 1981; see also Klein's 1999 view of expertise as involving 'recognition-primed' decision making). In contrast to experts, novices will have had limited opportunities to induce problem-solving schemas in a particular domain, such that they will frequently be unable to identify an appropriate schema for a given task. Faced with no available schema-based solution knowledge, novices will often have to rely on the heuristic of attempting to find a source analogue that shares surface similarities to the task at hand and that may have solution properties that can map successfully to the target. This is the process that we referred to above as case-driven analogising. It comes as little surprise, then, that novice problem solvers who have to default to this kind of strategy are typically seen to have difficulty in correctly categorising domain-based problems and deriving appropriate solutions for them (e.g., Chi et al. 1981)

Schema-based views of expertise have also been applied to the design domain, and have received some support as a way of characterising expert-novice differences in the areas of software design (e.g., Jeffries et al. 1981), architecture (e.g., Gero 1990), and engineering design (e.g., Ball, Evans and Dennis 1994). More recently, Ball et al. (2001) have gone as far as to argue that a fair proportion of expert designers' problem solving knowledge may be viewed as fairly 'routine' in nature, in that familiar kinds of problem will often have readily retrievable solutions or well-established 'precedents' (see Oxman, 1994) that are known to be effective. Still, a non-trivial proportion of design work, even for experts, is likely to involve tackling fairly non-routine problems, where highly schematised knowledge that has been induced from prior experience is simply not available. With such non-routine problems, the explicit search for some form of source analogue may (as in the novice case) prove to be the best strategy to use to facilitate a degree of progress in effecting a design solution. Thus, with non-routine aspects of design problems, both experts and novices should be seen to attempt case-driven analogising that will primarily be cued by surface-level associations between the target and available source cases. These theoretical speculations, however, require empirical assessment, and a major aspect of the study reported below was to evaluate such ideas experimentally. Before we progress to a description of our study we first reiterate, for the sake of clarity, the detailed predictions that underpinned our research.

2. Experimental predictions

Our examination of the literature on analogical reasoning and domain-based expertise enabled the derivation of two key predictions concerning expert-novice differences in the nature of analogising in design.

Prediction 1 was that experts would show more evidence of analogical reasoning than novices when measures of analogising were collapsed over the schema-driven and case-driven categories. This increase in expert analogising over novice levels was expected because experienced designers should possess vastly more knowledge of prior design problems and solutions that would have some bearing on the current problem-solving effort. Support for this prediction would arise as a *main effect* of level of expertise (i.e., expert vs. novice) in relation to observed levels of analogising occurring during design activity.

Prediction 2 was that expert design behaviour would be characterised by the presence of more schema-driven analogising than case-driven analogising, since, for experts, more domain-based problems should fall toward the familiar end of the familiar-unfamiliar continuum, and less toward the unfamiliar end. In the case of novices, however, the opposite pattern of schema-driven and case-driven analogising was expected to prevail, that is, less schema-driven analogising and more case driven analogising. This is because most problems would have limited familiarity to novices and would need to be approached using explicit, case-based reasoning. This prediction would show up in measures of analogising as an *interaction* between level of expertise (expert vs. novice) and form of analogising (schema-driven vs. case-driven).

It should be noted that for the purposes of the present paper we did not pursue any analyses of the 'quality' of analogising. Although it may be possible to derive relevant (and, no doubt, theoretically interesting) predictions about such qualitative aspects of analogical reasoning in expert and novice design, such issues are some way off our present focus on the differential forms and extent of analogising arising at distinct levels of design expertise.

3. Method

3.1. Participants

Eight expert designers and eight novice designers were recruited to participate in our study. The experts were all company-based engineers with a minimum of seven years of academic and commercial design experience (mean experience = 15.1 years). The novices were masters-level engineering students who had been involved in a limited number of design and development projects as part of their undergraduate and graduate work, including periods of company-based placement, occasionally up to a full year in duration. The mean amount of design experience of these student designers was 3.5 years. Although, in line with standard terminology, we use the term 'novice' to refer to our masters-level participants, it is important to acknowledge that these designers were some way along the continuum of design training, being more advanced than typical undergraduate designers but clearly more limited in their range of prior experience when compared to our company-based expert group. All participants were paid £15 for their involvement in the experiment.

3.2. Task

All participants received an identical brief that related to the design of an automated car-rental facility. This brief was designed to be complex, multifaceted and ill-defined in the traditional sense of a prototypical design problem (cf. Goel and Pirolli 1992), but tractable enough to be tackled to a satisfactory level by designers with only a few years of design experience. The brief requested a focus on product conceptualisation rather than detailed design, and necessitated that consideration be given to system inputs and outputs as well as constraints relating to usability, security, efficiency and the like. The car-rental problem read as follows:

> We would like you to come up with a product design concept for an Automated Rent-a-Car facility. The basic idea is that a national car rental agency has decided to improve the accessibility of their facilities to enable 24 hour availability for reservation of cars, and collection and return of keys. The vision is for a stand-alone, outdoor system that fulfils the following criteria: (1) Enables

reservation facilities by means of a keyboard interface; (2) Allows payment by credit card for deposit and final settlement; (3) Provides receipt of payment; (4) Checks driving licence details based on a new DVLA smart-card; (5) Arranges insurance cover; (6) Enables driver feedback on the external state of car prior to completion of the transaction; and (7) Dispenses keys and accepts return of keys. Your design work should be primarily focussed on the product concept and related issues (such as the external structure and appearance of the facility). Once the concept has been finalised the actual mechanics of the system (including software and hardware aspects) will become the concern of another design group that you would have input to.

3.3. Experimental design

The experiment involved a 2x2 mixed between-within participants design. The between-participants factor was Level of Expertise, with two levels (expert vs. novice), and the within-participants factor was Form of Analogising, with two levels (schema-driven vs. case-driven). The dependent measure in this study was the rate of different types of analogising observed during a participant's design work.

3.4. Procedure

Each participant was tested individually in a quiet setting. During their design session, the participant was asked to take one hour to complete a conceptual design solution that would meet the given brief as well as possible. Participants were free to make notes and to draw sketches as part of their design activity. Each participant was also asked to produce a concurrent think-aloud verbalisation during their design work, and was told that the experimenter was interested in capturing the initial phase of their typical design activity. If participants fell silent for more than five seconds they were prompted to try to keep thinking aloud. Verbalisations were recorded using a tape machine and all pen-and-paper work was recoded by means of a tripod-mounted video-camera.

3.5. Protocol coding

All participants produced highly articulate think-aloud protocols. Transcripts of these protocols were coded by the first author for all instances of schema-driven or case-driven analogising. Any repetitions or elaborations of the application of schema-based or case-based analogies were also coded as long as they were temporally separated from the original analogising episode with at least one different instance of analogising intervening between the original episode and the repetition or elaboration of the original analogy. All transcripts were coded blind as to the designer's level of expertise. Reliability checks on the protocol coding have, as yet, not been pursued, and it is, therefore, important to treat the present research findings with a concomitant degree of caution. It is noteworthy, however, that an application of a similar coding scheme to capture aspects of analogising in business-management protocols produced high levels of inter-coder reliability (see Bearman et al. 2002).

3.5.1. Coding of schema-driven analogising

In terms of the criteria underpinning the application of codes to protocol segments, it should be noted that we formally defined schema-driven analogising as arising *when a design problem was recognised as being of a particular kind that could be solved with a known type of solution approach.* For example, one of our experts stated early on in his design work that "I've designed outdoor terminals before, so, straight away, I'm thinking about how this relates to my knowledge of what I've done before…". This designer then progressed toward the conceptualisation of the overall task in terms of familiar 'principles' associated with the design of outdoor terminals, including generic factors that cut across the details of specific exemplars of such terminals such as weather-proofing, security, and the provision of cabling.

Another example of schema-driven analogising arose when one of our participants was working on the problem of how to position the screen-based interface within the rent-a-car facility. He immediately stated that "I know from experience that having a low, angled interface is the easiest thing to achieve, as tall people can look down, and shorter people don't have to try to access something that's too high for them. So we're looking for something with an angled display face". In this example, the designer was rapidly seen to conceptualise the positioning of the screen in terms of familiar principles associated with the design of accessible interfaces for outdoor terminals.

An important aspect of schema-driven analogising that was apparent in our data (and which can be seen to some extent in the example above) is that such analogising tended to entail a seamless process involving the mapping of the *abstract*, schema-based solution onto the *concrete* details of the current problem. So for example, whilst the previous schema incorporates the abstract notion of some kind of 'interface', in the actual design of the rent-a-car facility this generic concept of an interface may be instantiated as a specific kind of screen display (e.g., a touch-screen).

3.5.2. Coding of case-driven analogising

In contrast to schema-driven analogising, we formally coded protocol segments as instances of case-driven analogising *when a design problem was recognised as being similar to one or more specific 'instances' of a problem or situation that had been encountered on a prior occasion, and was solved with reference to such similarities*. For example, one of our participants stated that "I'm thinking immediately back here to a ticket machine that we worked on, where an external consultant came up with the idea of a rotary wheel for scrolling through the screen options". Here the designer was drawing an explicit link between the current design task (i.e., to decide on a device for scrolling through and selecting a screen item) and an analogous problem and its solution.

A central aspect of case-driven analogising that was evident in our design protocols was that it invariably involved a systematic process of mapping from elements of the source problem and solution in order to effect a solution to the target problem. So for example, one designer drew an association between the way credit-card bookings can take place for cinema tickets and a potential solution for the problem of making an advanced car reservation. Using this source analogy the designer explicitly mapped the idea of telephoning the cinema with card details and then using an automated ticket machine on arrival at the cinema onto the concept of making a car-reservation via the telephone and then using a credit card to obtain the car-keys on arrival at the rent-a-car facility. Another example of case-driven analogising that illustrates this mapping process arose when one of our experts speculated on a possible design for a mechatronic system to handle car keys within the rent-a-car facility. He described the possibility of using a piece of robotics "…like one of those laundry automation set-ups where you go to collect your suit from the cleaners and there's a robot – you just feed in a card and it runs along and picks up your piece of cleaning…". He mapped this source solution to the key-handling problem by stating that "…you might imagine that the keys hang on a series of little pegs by this, inside some, some cupboard, and inside it's got some tiny robot that goes dodododododo and picks this key off and then brings it back and then drops it down a chute…".

4. Results and discussion

Coded protocols were processed further in order to extract frequency counts for each individual designer of the occurrence of discrete instances of schema-driven analogising and case-driven analogising. Individual scores on each of these measures were then adjusted to take account of the exact amount of time that the designer had taken over their design session (i.e., although designers were requested to complete their design work within an hour, some took marginally shorter or longer amounts of time than this, with the range of total design time being from 40 minutes at a minimum to 75 minutes at a maximum). Adjusting frequency counts of schema-driven and case-driven analogising to take account of such individual differences in time-on-task simply entailed computing, for each designer, an estimate of the rate of each type of analogising *per hour* of design time. Mean data resulting from these adjustments are presented in Table 1 below.

From Table 1 it can be seen that the mean rate of analogising was greater for experts than for novices (32.2 vs. 22.9 analogies per hour). Analysis of variance (ANOVA) revealed that this expert-novice difference in analogising was statistically reliable, $F(1, 14) = 5.04$, $p = .041$. This finding supports *Prediction 1*, that is, that experts should show greater evidence of analogical reasoning than novices, irrespective of whether such analogising is schema-driven or case-driven in form. This prediction derived from our assumption that experts possess vastly more knowledge than novices of prior design problems and solutions that should have some use for the current problem-solving effort.

Table 1 - Mean rate of analogising (i.e., analogies generated per hour) as a function of Level of Expertise and Form of Analogising (N = 16; standard deviations in parentheses)

	Schema-Driven	Case-Driven	*Mean*
Experts	53.1 (11.5)	11.3 (7.7)	32.2
Novices	16.5 (8.8)	29.4 (10.7)	22.9
Mean	34.8	20.3	

Table 1 also indicates that schema-driven analogising was more prevalent in the present designers' work than was case driven analogising (34.8 schema-driven analogies per hour vs. 20.3 case-driven analogies per hour). This main effect of Form of Analogising was highly reliable, $F(1, 14) = 31.24$, $p < .001$. Although we did not specify any a priori prediction concerning the overall rates of schema-driven versus case-driven analogising, it is clear from Table 1 that this effect results from the dominant role that schema-driven analogising plays in expert design practice in the present design context. Indeed, any detailed theoretical assessment of our findings needs to take account of the fact that our data analysis revealed a highly significant cross-over interaction between Level of Expertise and Form of Analogising, $F(1, 14) = 111.33$, $p < .001$. This interaction was as expected under *Prediction 2*, that is, that expert design behaviour would be characterised by the presence of more schema-driven analogising than case-driven analogising, since, for experts, more domain-based problems should be familiar and have known types or categories of solution possibilities that have been abstracted from extensive domain-based experience. For novices, however, the opposite pattern of schema-driven and case-driven analogising was expected to arise, that is, less schema-driven analogising and more case-driven analogising. This is because most problems would have only limited familiarity to novices and would, therefore, need to be attempted using explicit and concrete forms of case-based reasoning. The data depicted in Table 1 are very much in line with these assumptions about expert-novice differences in design-based analogising.

A final aspect of our data that is also worth mentioning is that a majority of the case-driven analogising that we identified in both the expert and the novice protocols appeared to be dominated by the use of surface-level cues available in the target problem, as opposed to more abstract cues associated with the underlying structure of the target. This informal observation lends some support to the theoretical ideas that we outlined in our introductory review of the analogising literature which suggest that surface similarity between target and source problems is particularly crucial in promoting spontaneous analogical reasoning (e.g., Blessing and Ross 1996, Sweller 1980).

5. Conclusions

In this paper we set out to investigate the extent and nature of spontaneous analogical reasoning associated with novice and expert design activity. In terms of theories of design problem-solving and expert cognition, we believe that our results are important in three main respects.

First, they demonstrate the prevalence of spontaneous analogising in both expert and novice design practice. This finding corroborates the widely-held assumption that analogising plays a fundamental role in creative, real-world problem solving (e.g., Holyoak and Thagard 1995). It would appear that analogising is part of the natural behavioural repertoire of industrial designers, and is a form of reasoning that can flourish without directive hints from the experimenter that explicitly request the reuse of prior knowledge and experience.

Second, our findings clarify that expert designers exhibit more schema-driven analogising than case-driven analogising, whilst novices show the reverse pattern of analogy use. This supports existing theories of domain-based expertise (e.g., Anderson 1989, Chi et al. 1981) which suggest that a critical aspect of skill acquisition is a move from initial reliance on specific, concrete episodes of prior domain experience toward the application of highly schematised knowledge structures based on the automatic recognition of familiar types or categories of problems and solutions. Of course, the novice-level application of specific cases to current design tasks is a vital and necessary aspect of the whole process of knowledge schematisation that eventually leads to expert-levels of skilled design work. Our data also indicate, however, that the use of case-driven design is still an important aspect of expert behaviour. This reveals that even experts designers with many years of professional domain-based experience will find numerous aspects of design problems unfamiliar and resistant to schema-based processing. Indeed design problems are notorious for possessing nuances and complexities that render the use of routine solutions ineffective. When schematised knowledge cannot be applied then experts seem to be readily capable of defaulting to the use of case-based experience in order to progress their problem-solving activity.

Third, our data suggest that the numerous instances of case-driven analogising that are evidenced by expert and novice designers are dominated by the use of surface-level cues available in the target problem, as opposed to more abstract cues associated with the target's underlying problem structure. This latter, anecdotal observation substantiates theoretical ideas that we outlined in our introductory review of the analogising literature, which suggest that surface similarity between target and source problems is particularly crucial in promoting spontaneous analogical reasoning (Blessing and Ross 1996, Sweller 1980). Further research on case-based analogising in design would benefit from a formal approach to examining the relative role of surface-level details and deep-level abstractions in promoting the search for source analogues and the mapping between such source information and target problems. As Visser (1996) notes, however, defining precisely what constitute surface-level and abstract similarities between design problems is likely to be a non-trivial matter.

Acknowledgements

We gratefully acknowledge the contributions made by our participants to this research. Aspects of this work were supported by an ESRC Cognitive Engineering Grant awarded to Linden Ball, Tom Ormerod and John Mariani (Grant Ref: L127251027).

References

Anderson, J. R. (1989) The Analogical Origins of Errors in Problem Solving, in Klahr, D. and Kotovsky, K. (eds.) Complex Information Processing: The Impact of Herbert A. Simon, Hillsdale, NJ, LEA, pp 343-371.

Anoli, L., Antonietti, A., Crisafulli, L. and Cantoia, M. (2001) Accessing Source Information in Analogical Problem-Solving, Quarterly Journal of Experimental Psychology, 54A, pp 237-261.

Ball, L. J., Evans, J. St. B. T. and Dennis, I. (1994) Cognitive Processes in Engineering Design: A Longitudinal Study, Ergonomics, 37, pp 1753-1786.

Ball, L. J., Evans, J. St. B. T., Dennis, I. and Ormerod, T.C. (1997) Problem-Solving Strategies and Expertise in Engineering Design, Thinking and Reasoning, 3, pp 247-270.

Ball, L. J., Lambell, N. J., Reed, S. E. and Reid, F. J. M. (2001). The Exploration of Solution Options in Design: A 'Naturalistic Decision Making' Perspective, in Lloyd, P. and Christiaans, H. (eds.) Designing in Context: Proceedings of the Fifth Design Thinking Research Symposium—DTRS 5, Delft, The Netherlands, Delft University Press, pp 79-93.

Bearman, C. R., Ball, L. J. and Ormerod, T. C. (2002) An Exploration of Real-World Analogical Problem Solving in Novices, in Gray, W. D. and Schunn, C. (eds.) Proceedings of the Twenty-Fourth Annual Conference of the Cognitive Science Society, Mahwah, NJ, LEA, pp 101-106.

Blanchette, I. and Dunbar, K. (2000) How Analogies are Generated: The Roles of Structural and Superficial Similarity, Memory and Cognition, 28, pp 108-124.

Blessing, S. B. and Ross, B. H. (1996) Content Effects in Problem Categorization and Problem Solving, Journal of Experimental Psychology: Learning, Memory, and Cognition, 22, pp 792-810.

Casakin, H. and Goldschmidt, G. (1999) Expertise and the Use of Visual Analogy: Implications for Design Education, Design Studies, 20, pp 153-175.

Catrambone, R. and Holyoak, K. J. (1989) Overcoming Contextual Limitations on Problem-Solving Transfer, Journal of Experimental Psychology: Learning, Memory, and Cognition, 15, pp 1147-1156.

Chi, M. T. H., Feltovich, P. J. and Glaser, R. (1981) Categorization and Representation of Physics Problems by Experts and Novices, Cognitive Science, 5, pp 121-152.

Cross, N., Christiaans, H. and Dorst, K. (eds.) (1996) Analysing Design Activity, Chichester, Wiley.

Dunbar, K. and Blanchette, I (2001) The *In Vivo/In Vitro* Approach to Cognition: The Case of Analogy, Trends in Cognitive Sciences, 5, pp 334-339.

Gero, J. (1990) Design Prototypes: A Knowledge Representation Schema for Design, AI Magazine, 11, pp 26-36.

Gick, M. L. and Holyoak, K. J. (1980) Analogical Problem Solving, Cognitive Psychology, 12, pp 306-355.

Gick, M. L. and Holyoak, K. J. (1983) Schema Induction and Analogical Transfer. Cognitive Psychology, 15, pp 1-38.

Goel, V. and Pirolli, P. (1992) The Structure of Design Problem Spaces, Cognitive Science, 16, pp 395-429.

Holyoak, K. J. and Koh, K. (1987) Surface and Structural Similarity in Analogical Transfer, Memory and Cognition, 15, pp 332-340.

Holyoak, K. J. and Thagard, P. (1995) Mental Leaps: Analogy in Creative Thought, Cambridge, MA, MIT Press.

Jeffries, R., Turner, A. A., Polson, P. G. and Atwood, M. E. (1981) The Processes Involved in Designing Software, in Anderson, J. R. (ed.) Cognitive Skills and their Acquisition, Hillsdale, NJ, LEA, pp 255-283.

Keane, M. (1987) On Retrieving Analogues when Solving Problems, Quarterly Journal of Experimental Psychology, 39A, pp 29-41.

Klein, G. (1999) Sources of Power: How People Make Decisions, Cambridge, MA, MIT Press.

Kolodner J. (1993) Case-Based Reasoning, San Mateo, CA, Morgan-Kaufmann.

Novick, L. R. (1988) Analogical Transfer, Problem Similarity and Expertise, Journal of Experimental Psychology: Learning, Memory and Cognition, 14, pp 510-520.

Oxman, R. E. (1994) Precedents in Design: A Computational Model for the Organization of Precedent Knowledge, Design Studies, 15, pp 141-157.

Pedone, R., Hummel, J. E. and Holyoak, K. J. (2001) The Use of Diagrams in Analogical Problem Solving, Memory and Cognition, 29, pp 214-221.

Raven, J. C. (1938) Progressive Matrices: A Perceptual Test of Intelligence, London, Lewis.

Schank, R. C. (1999) Dynamic Memory Revisited, Cambridge, UK, Cambridge University Press.

Simon, H. A. (1981) The Sciences of the Artificial (2nd Edition), Cambridge, MA, MIT Press.

Sternberg, R. J. (1977) Component Processes in Analogical Reasoning, Psychological Review, 84, pp 353-378.

Sweller, J. (1980) Transfer Effects in a Problem Solving Context, Quarterly Journal of Experimental Psychology, 32, pp 233-239.

Thompson, L., Gentner, D. and Loewenstein, J. (2000) Avoiding Missed Opportunities in Managerial Life: Analogical Training More Powerful than Individual Case Training. Organizational Behavior and Human Decision Processes, 82, pp 60-75.

Visser, W. (1996) Use of Episodic Knowledge and Information in Design Problem Solving, in Cross, N., Christiaans, H. and Dorst, K. (eds.) Analysing Design Activity, pp 271-289, Chichester, Wiley.