# *Analogical reasoning and mental simulation in design: two strategies linked to uncertainty resolution*

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*This paper aims to further an understanding of the nature and function of analogising and mental simulation in design through an analysis of the transcripts of two engineering design meetings. Analogies were coded for 'purpose' and in terms of whether they were within-domain or between-domain. Mental simulations were coded for 'focus': technical/functional or end-user. All expressions of uncertainty were also identified. Analogies were found to be typically between-domain (indicative of innovative reasoning) and were evenly distributed across solution generation, function finding and explanation. Mental simulations were predominantly technical/functional. Our most striking observation was that analogies and mental simulations were associated with conditions of uncertainty. We propose that analogising and mental simulation are strategies deployed to resolve uncertainty — a claim that is supported by the fact that uncertainty levels returned to baseline values at the end of analogising and simulation episodes.*


*Keywords: analogical reasoning, mental simulation, uncertainty resolution, design strategies, engineering design*

Analogical reasoning involves accessing and transferring previously acquired knowledge of objects, attributes and relations to support current problem solving and decision making activities. Such reasoning has long been viewed as central to intelligent thought and creative cognition (Gentner and Stevens, 1983; Holyoak and Thagard, 1995; Schank, 1999), with recent studies confirming the importance of analogising for scientific discovery (Dunbar and Blanchette, 2001), organisational management (Bearman et al., 2007), and innovative product development (Visser, 1996; Casakin and Goldschmidt, 1999; Ball et al., 2004; Casakin, 2004). A recent study by Christensen and Schunn (2007) has further clarified the key characteristics of analogising in design via a detailed 'in vivo' examination of design meetings in an international R&D company specialising in the design of medical plastics. Around 9 h of discussion by a core design team was analysed, with transcripts

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spanning the first five months of a design project. Christensen and Schunn's (2007) analysis indicated that analogising was a frequent strategy deployed by the team, with analogies serving three primary functions or purposes: problem identification, problem solving, and explaining (cf. Bearman et al.'s, 2007, evidence for two primary functions of analogising in management decision making: problem solving and illustration). In addition to their function-oriented characterisation of design analogies, Christensen and Schunn (2007) also coded analogies in terms of their 'distance' from the domain of medical plastics. Using a binary classification system of *within-domain* versus *between-domain* they revealed that within-domain analogies prevailed during problem identification, whilst between-domain analogies prevailed during explanation. In contrast, solution generation was characterised by an equal distribution of within-domain and between-domain analogies.

The DTRS7 dataset afforded an opportunity to delve further into issues surrounding analogising in design. By focusing on the engineering meetings (E1 and E2) we aimed to replicate and extend Christensen and Schunn's (2007) evidence that analogies are used for different purposes in innovative design situations. Likewise, we wished to validate the links between analogical purpose and analogical distance. Finally, we aimed to examine the relation between analogising and 'epistemic uncertainty'. The latter concept refers to situations where people have metacognitive awareness of the limitations of their current knowledge or understanding (e.g., Davidson et al., 1996; Quayle and Ball, 2000). Epistemic uncertainty is integral to non-routine design contexts (Schlosser and Paredis, 2007), where the complex, multi-facetted and ill-defined nature of problems means that designers are continually working at the extremity of their current knowledge. One idea that we wanted to examine was whether analogising may be a strategy that is deployed under conditions of uncertainty in order to reduce or resolve such uncertainty. For example, designers may use analogies to enhance their grasp of poorly understood design requirements and constraints, to clarify the nature of ill-defined problems, to inform the completion of partially developed solution concepts, or to augment the communication of vague ideas.

In addition to inspecting the engineering transcripts for instances of analogising we also aimed to examine them for evidence of another cognitive strategy, 'mental simulation', where a sequence of interdependent events is consciously enacted or 'run' in a dynamic *mental model* to determine cause-effect relationships and to predict likely outcomes (Gentner, 2002; Nersessian, 2002). Model-based mental simulation appears to be primarily an *evaluative* strategy, where the designer's imagination is used to test out ideas and validate solution concepts. There are certainly striking personal accounts in the literature signifying the importance of mental simulation in design and architecture. For example, Frank Lloyd Wright's famous anecdote of the design for Fallingwater (one of the USA's most acclaimed residential buildings) indicates that before committing ideas to the drafting board he was able to: 'Conceive the building in the imagination, not on paper but in the mind, thoroughly…' (Tafel, 1979).

The mental models that underpin the process of mental simulation are assumed to involve qualitative rather than quantitative reasoning, relying, for example, on ordinal relationships and relative judgements (Forbus, 1997). Thus when running mental models people neither estimate precise values and quantities nor carry out mathematical computations in predicting device behaviour. Despite lacking a focus on exact quantifications, however, such mental simulations can be very powerful, having the great advantage of facilitating the process of reasoning on the basis of incomplete knowledge. In mechanical domains there is also evidence that the inferential processes associated with mental models are modal and analogous to the physical properties of the systems and processes being simulated (Hegarty and Just, 1993; Schwartz and Black, 1996; Hegarty et al., 2003). In essence, then, mental simulation provides a relatively quick and cognitively economical way for an individual to test out the behaviour of a physical system, including how a system might function under changed circumstances or with altered features.

In strategic terms mental simulation would seem to be especially useful in creative domains such as science and design, where tasks involve constructing novel solutions within a large space of possibilities. Previous studies using verbal protocol analysis have confirmed the important role of mental simulation in both domains. For example, Trickett et al. (2005) located the presence of mental model 'runs' in the protocols of scientists conducting data analysis, whilst Christensen and Schunn (in press-b) identified key instances of mental simulation in design protocols. The latter research tested three core assumptions of mental simulation theories: that mental simulations are run under situations associated with subjective uncertainty; that mental simulations of possibilities inform reality through inferences that reduce uncertainty; and that the role of mental simulations is approximate and inexact. Christensen and Schunn (in press-b) successfully demonstrated support for all three assumptions: initial representations in simulations had higher than baseline levels of uncertainty; uncertainty was reduced after the simulation run; and resulting representations contained more 'approximate' references than either baseline data or initial representations. The DTRS7 dataset (described in more detail in the editorial section of this issue) presented an opportunity to examine further the links between mental simulation and uncertainty in an attempt to generalise and extend Christensen and Schunn's (in press-b) findings.

In summary, our aims in the work presented here were to pursue a detailed protocol analysis of the transcripts of the two engineering meetings in order to further an understanding of how mental simulation and analogising may be linked to epistemic uncertainty. Although the analyses that we present below follow on closely from previous research we note that our approach departs from earlier studies in terms of both the intended *breadth* of interest on the three concepts of analogising, mental simulation and uncertainty, and the intended *depth* of analysis in relation to the nature and function of different 'types' of analogising and mental simulation.

## 1 Transcript coding

In order to divide up the engineering meetings of the DTRS7 dataset into discrete units of spoken discourse we decided to use the line-based segmentation scheme already present in the meeting transcripts. Our analysis, therefore, involved a total of 3886 line-segments of data (henceforth simply referred to as 'segments'). Below we describe the approach that we adopted to code the protocols for occurrences of analogies, mental simulation and epistemic uncertainty. Individual codes appear in SMALL CAPS.

### 1.1 Coding of analogies

The transcripts were coded for presence of ANALOGY by applying Christensen and Schunn's (2007) approach. Any time a designer referred to another source of knowledge and attempted to transfer concepts from that source to the target domain then this reference was coded as an analogy. All analogies were also coded for ANALOGICAL DISTANCE using a binary categorisation scheme where *within-domain* analogies involved mappings from sources that related to tools, mechanisms and processes associated with graphical production and printing, whilst *between-domain* analogies involved mappings from more distant sources (see Extracts 1 and 2).

**Extract 1 E1, Example of within-domain analogy**

| | | |
|---|---|---|
| 819 | Alan | the other thing to to think about is in almost all cases when I look at pens |
| 820 | | the apart from re-wired sort of micropens the th- tip is actually the |
| 821 | | narrowest part of the product whereas in what we're looking at it could |
| 822 | | actually be as wide or wider- |

**Extract 2 E2, Example of between-domain analogy**

| | | |
|---|---|---|
| 247 | | a pen that looks like this and you just put water in it um er the best |
| 248 | | analogy I can think of is er if you like wet t-shirt eect where- |
| 249 | All | [*laugh*] |
| 250 | Tommy | the top layer the top layer of paper gets wet |
| 251 | Sandra | [*laughs*] |
| 252 | Tommy | the top layer of material gets wet and reveals what's underneath it |
| 253 | Sandra | oh right |

We also coded analogies for ANALOGICAL PURPOSE (i.e., the goal or function of the analogy) using a tripartite scheme based on that developed by Christensen and Schunn (2007). This scheme (see Extracts 3–5) categorised analogical purpose in terms of:

- *problem identification* – noticing a possible problem in the emerging design, where the problem was taken from an analogous source domain
- *solution generation* – transferring possible solution concepts from the source domain to the target domain
- *explanation* – using a concept from the source domain to explain some aspect of the target domain to members of the design team.

**Extract 3 E1, Example of problem identification analogy**

| | | |
|---|---|---|
| 1026 | Alan | in fact in some ways we should think about the fact it isn't even a pen |
| 1027 | | because a pen you you'll always learn to write from left to right whether |
| 1028 | | you're left handed or right handed so actually what you end up doing is |
| 1029 | | left handed people is you smudge over over your work which is a problem |
| 1030 | | but actually with this you're dragging it you're not pushing it are you |
| 1031 | | most people will drag it |

**Extract 4 E1, Example of solution-generation analogy**

| | | |
|---|---|---|
| 1291 | Tommy | like a garage door type of thing |
| 1292 | Tod | yeah push the button then it goes open |
| 1294 | Tod | but that's probably overly complicated |
| 1295 | Rodney | garage door well it could be a roller |
| 1296 | Tod | a roller door |

**Extract 5 E2, Example of explanation analogy**

| | | |
|---|---|---|
| 172 | Tommy | yeah this is a bit like photographic paper in a way where you're erm |
| 173 | | developing what's on the paper whereas here you're just enabling the bits |
| 174 | | you need to print so here you're kind of getting in to normal text |

**Extract 6 E1, Example of function-finding analogy**

| | | |
|---|---|---|
| 986 | Tod | um that's intriguing sort of like a like a could be like a finger puppet |
| 987 | | couldn't it |
| 988 | Sandra | yeah cos wearing it like a finger puppet – the feel of it might be fun |
| 989 | Tod | exactly so you can make you can make the footprints- |
| 990 | Rodney | I I think I think the sort of design not very good at () |

During the application of this a priori coding scheme, however, we found that a significant number of analogies were not readily categorisable as oriented toward problem identification, solution generation or explanation. Thus a new analogy purpose emerged from the transcripts relating to situations involving the active mapping of *new functions* to the *design form* currently being developed (i.e., a thermal printing pen). We refer to this new analogy type as *function finding* (see Extract 6). With the addition of this category to the scheme it was possible to code all analogies within the transcripts.

## 1.2 Coding of mental simulations

The codes relating to the presence of MENTAL SIMULATION were based on those developed by Christensen and Schunn (in press-b), which were, themselves, adapted from Trickett and Trafton (2002). A mental model 'run' is taken to be a mentally constructed model of a situation, phenomenon, object or system of objects that is grounded either in memory or in the mental modification of design artefacts that are currently present. As such, mental simulation enables designers to reason about new possible states of a design artefact in terms of its perceptual qualities, functions, features or attributes, but without the need for

**Extract 7 E1, Example of technical/functional simulation**

| | | |
|---|---|---|
| 1755 | Tommy | there's two forces there isn't there [*bangs it*] there's sort of the |
| 1756 | | momentum of the thing itself |
| 1757 | Alan | mmm |
| 1758 | Tommy | yeah it's not going to be anything like this heavy is it |
| 1759 | Jack | no well as I say you need to shock that down () |
| 1760 | | +++ |
| 1761 | Tommy | er |
| 1762 | Jack | you're smash you're gonna smash the edge of this protective sheath |
| 1763 | | before this does anything in here |
| 1764 | Tommy | yeah also they're not that () made out of ceramic and glass |
| 1765 | Jack | mmm I think that's-I think that the other other protective thing is whether |
| 1766 | | they smash it o the table before momentum |

**Extract 8 E1, Example of end-user simulation**

| | | |
|---|---|---|
| 691 | Rodney | I think if I was in their shoes using this I'd prefer they'd be something where |
| 692 | | I decide whether it's in the right position or whether I want something |
| 693 | | lighting up and saying der-derrr- |
| 694 | Alan | mmm |
| 695 | Rodney | that kind of thing |
| 696 | Alan | well there's a bit of training there isn't it |
| 697 | Rodney | true but it it's kind of patronising to have these sort of lights |

physical manipulation of the actual artefact. Mental simulations are not limited merely to technical design properties, but can also relate to envisioning a whole range of changed circumstances, including those arising from end-user interactions with the design artefact. We coded SIMULATION TYPE in the present transcripts using a binary scheme (see Extracts 7 and 8) whereby simulations related either to: technical/functional aspects of the product (e.g., altering its form, function, or features); or end-user behaviour associated with the product (e.g., people's use habits, usability comprehension, or interaction experience).

Notwithstanding the different foci of mental simulations, their key feature involves a simulation 'run' that alters mental representations to produce a change of state. What this means is that mental simulations entail a specific sequence of representational changes, beginning with the creation of an initial representation, then involving the running of that representation (where it is modified by spatial transformations where elements or functions may be extended, added to, deleted, etc.), and ending up with a final, altered representation (Christensen and Schunn, in press-b). These three elements (initial representation, simulation run, and changed representation) are not mutually exclusive, but could occur in the same protocol segment in the present transcripts, although typically they extended over several segments.

### 1.3 Coding of uncertainty

Epistemic UNCERTAINTY was coded using a purely syntactic approach – adapted from Trickett et al. (2005) and Christensen and Schunn (in press-b) – which employs 'hedge words' to locate segments displaying uncertainty. In the present analysis these hedge words included terms like 'probably', 'sort of', 'guess', 'maybe', 'possibly', 'don't know', '[don't] think', '[not] certain' and 'believe'. Segments containing these words were located and were coded

**Extract 9 E1, Example of an 'uncertainty present' segment (bold typeface) and an 'uncertainty absent' segment (normal typeface)**

| | | |
|---|---|---|
| 1592 | Tod | my arg what I was trying to say before is erm you could do it with one |
| 1593 | | switch if if the casework say the casework is comes out f-further out errm |
| **1594** | | **+++ it may or may not work erm [*clears throat*] if you what it does is you've** |
| 1595 | | got one switch that if it's but if it's on and back i-it works but then if you pivot |
| 1596 | | pivot this can pivot a bit but it but it pivots more on the c- but the case |
| 1597 | | if you pivot a little bit on the c-the case comes in contact and it starts to |
| 1598 | | come away |

**Table 1 Kappa coefficients for inter-coder reliability**

| Coding category | Kappa coefficient |
|---|---|
| UNCERTAINTY | .88 |
| ANALOGY | .77 |
| ANALOGICAL PURPOSE | .85 |
| ANALOGICAL DISTANCE | .99 |
| MENTAL SIMULATION | .75 |
| SIMULATION TYPE | .71 |

as *uncertainty present* – but only if it was also clear that the hedge words were not simply being stated as politeness markers by members of the design team. All segments that were not coded as *uncertainty present* were coded as *uncertainty absent* (see Extract 9 for an example). Segments containing uncertainty made up 13% of the dataset.

### 1.4 Inter-coder reliability checks

The second author acted as primary coder. To assess coding consistency an individual who was not associated with this research coded 1 h of data (segments 500–1771 from E1). This independent coder received general training in protocol analysis and was also given some familiarisation and practice with the present coding categories using 'spare' data from the transcripts. All coding categories reached acceptable levels of reliability (i.e., greater than .70), with near perfect reliability for analogy type. Kappa reliability coefficients are reported in Table 1.

## 2 Results and discussion

### 2.1 Analogies

Across the two transcripts we identified 147 unique analogies, which ranged from 1 to 20 segments, averaging 3.5 segments per analogy. Analogies thus made up 13% of the segments across E1 and E2 and are clearly used frequently by the present designers during their product development meetings.

### 2.2 Analogical distance

Of the 147 analogies produced the vast majority (84%) were *between-domain*, with 16% *within-domain*. Previous evidence (Dahl and Moreau, 2002; Christensen and Schunn, in press-a) suggests that distant analogies have a positive effect on the estimated originality of resulting product designs. Thus our observation of very high levels of distant analogising in the present context may indicate that an elevated level of innovative design was taking place. Our findings here contrast with Christensen and Schunn's (2007) results, which revealed that *within-domain* and *between-domain* analogies were equally distributed across team design meetings in the area of medical plastics. Such discrepant findings may reflect domain differences between engineering sub-disciplines; alternatively, this discrepancy may have a basis in the different goals of the meetings in the two studies. In the present case the designers were primarily engaged in brainstorming activities aimed at solving problems associated with the print head mounting and pen format. Such brainstorming – with its emphasis on the creative exploration of the design space – may well encourage a focus on distant analogies rather than close ones. In addition, the present designers had been specifically requested prior to E1 to do some 'homework' so that they could come prepared with 'a product (or a picture of a product) that has to glide smoothly over contours'. This request would be likely to focus the designers on distant analogies rather than within-domain ones. In Christensen and Schunn's (2007) study, in contrast, the designers were developing improvements to an existing product; this may have encouraged more within-domain analogising linked to aspects of similar products, rather than far-flung between-domain analogising.

## 2.3 Analogical purpose

Analogies were fairly evenly distributed in terms of their purpose across the categories of *solution generation* (37%), *function finding* (33%) and *explanation* (27%), with only a minority being directed toward *problem identification* (3%). The level of analogy-based problem identification in the present study is markedly lower than that observed by Christensen and Schunn (2007), and, we wonder if this may again be a consequence of discrepancies in the broader goals of the project meetings in the two studies. In particular, since Christensen and Schunn's designers were striving to refine an existing product, then it makes perfect sense that problem identification would have been a key activity that could have been bootstrapped through analogising. In the present study, however, problem identification was arguably not a priority since for both of the engineering meetings a number of 'problems' had already been presented to the design team as givens. For example, in relation to E1 a set of four problems had been stipulated in advance as a focus for the meeting, namely, keeping the print head level; protecting the print head; activating the print head; and constraining the print head angle. It is unlikely, then, that these pre-identified problems would have fuelled any further analogy-based problem identification. Instead, analogy-based solution generation and explanation would have been the more likely outcome of having been presented with problems to solve as part of the design brief (which is precisely what was observed).

Despite the plausibility of these proposals we note that the high prevalence of *function finding* as a form of analogising in the present protocols is curious given that the purpose of such analogising has little to do with actually solving pre-identified problems. This type of analogising – which we believe has not previously been discovered in the literature – was observed when designers actively searched for novel ways in which the thermal printing pen might operate, and involved the mapping of a potential *function* from a source domain onto the existing design *form* in the target domain. Such analogising, whilst

**Table 2 Distribution of analogy types across 'function-before-form' and 'form-before-function' episodes**

| | Function-before-form episodes | Form-before-function episodes |
|---|---|---|
| *problem identification* | 5 | 0 |
| *solution generation* | 52 | 1 |
| *explanation* | 30 | 10 |
| *function finding* | 6 | 43 |

not specifically related to problem solving, may well have been a consequence of the remit of these meetings as being to engage in brainstorming, the very point of which is to pursue a creative exploration of the design space. Although much of the brainstorming in the present meetings was focused on the required set of 'problems' that needed to be solved, it appears that the team's brainstorming also transitioned (either strategically or inadvertently) into phases of exploratory concept generation fuelled by function-finding analogies.

This latter *form-before-function* activity involved designers taking the novel mechanical form and reflecting on what could be done with it in terms of functions. This is a very different process to 'design-as-usual', which progresses in a *function-before-form* manner, where functional requirements need to be realised as a blueprint for an implementable artefact. To examine further the relation between different types of analogising and different types of design activity we coded transcripts in terms of the overall *design question* being pursued. In this way we were able to identify two primary types of design episode: a single form-before-function episode and three function-before-form episodes. (NB: Two other episodes related to 'introductory comments' and were excluded from the analysis.) The distribution of analogies across these two episode types is shown in Table 2. It is apparent that the episode where designers were seeking new functions for the existing form was associated with nearly all of the function-finding analogies and relatively few of the other types of analogies, an effect that was highly reliable with a chi-square analysis, $\chi^2(3) = 87.85$, $p < .001$.

**Table 3 Mean analogical distance scores (plus standard deviations) for analogy types**

| | Mean | Standard deviation |
|---|---|---|
| *problem identification* | 1.00 | .00 |
| *solution generation* | 1.80 | .41 |
| *explanation* | 1.83 | .38 |
| *function finding* | 1.98 | .14 |

**Table 4 Number of segments revealing presence versus absence of uncertainty before, during and after analogies as well as for baseline segments**

| | *uncertainty absent* | *uncertainty present* |
|---|---|---|
| Baseline segments | 2325 | 325 |
| Five segments before analogy | 309 | 49 |
| Segments during analogy | 421 | 93 |
| Five segments after analogy | 313 | 51 |

## 2.4 The relation between analogical distance and analogical purpose

It is also of interest to know whether the analogical distance parameter (i.e., the extent to which analogies are *within-domain* or *between-domain*) varies in relation to analogical purpose. To examine this issue we conducted a one-way Analysis of Variance (ANOVA), with analogical distance as the dependent variable (1 = within-domain; 2 = between-domain) and with analogical purpose as the independent variable (see Table 3 for descriptive data). This analysis revealed a reliable effect of analogical purpose, $F(3,146) = 14.04$, $p < .001$. From Table 3 it is apparent that analogies linked to problem identification were exclusively *within-domain*, whilst all other analogy types were predominantly *between-domain*, with function-finding analogies being markedly between-domain in nature. Post hoc analyses using Tukey HSD tests confirmed that *problem identification* analogies were significantly different in analogical distance to all other analogies ($p$s $< .001$). *Function-finding* analogies were also significantly different to *solution-generation* analogies ($p = .03$), being more *between-domain* in nature.

## 2.5 Analogies and uncertainty

Our analysis also explored the existence of a possible association between analogising and epistemic uncertainty. We applied the binary scheme described previously to categorise all protocol segments in terms of presence or absence of uncertainty. Our analysis then focused on the number of segments during analogies that showed either presence or absence of uncertainty, and compared these values with those for the five segments before the analogy, the five segments after the analogy, and all remaining segments (the latter providing a baseline measure). Table 4 indicates that only analogies had uncertainty levels that were elevated above baseline, an effect that was reliable with

**Table 5 Number of *simulation present* and *simulation absent* segments revealing presence versus absence of uncertainty**

| | *uncertainty absent* | *uncertainty present* |
|---|---|---|
| *simulation present* | 892 | 202 |
| *simulation absent* | 2476 | 316 |

a chi-square analysis, $\chi^2(3) = 12.89$, $p < .005$. This very tight temporal coupling between analogising and uncertainty suggests that analogies are instantiated *coincident* with situations of design uncertainty whilst also facilitating the *resolution* of such uncertainty (since post-analogy segments resume baseline uncertainty levels). This makes a lot of sense in that analogising involves exploratory reasoning about concepts and mappings that are synchronised to deal with immediate design uncertainties, with these concepts and mappings typically being helpful in removing doubts and improving understanding.

## 2.6 Mental simulation

Across the two engineering transcripts we located 130 unique mental simulations (83 technical/functional; 47 end-user). These ranged from 3 to 25 segments, averaging at 8.4 segments per simulation. Simulations thus made up 28% of the segments within the transcripts. Of the 130 simulations, 124 contained identifiable segments for all three simulation parts: initial representation, simulation run, resulting representation.

## 2.7 Mental simulation and uncertainty

To examine whether mental simulations are associated with epistemic uncertainty we compared the coded segments that had been categorised in terms of the presence or absence of uncertainty (see Section 2.5 above) with the segments where simulation was present or where simulation was absent. The data from this analysis are presented in Table 5. It is evident that segments where simulation was present show a higher association with uncertainty compared to segments where simulation was absent. This effect was highly reliable with a chi-square analysis, $\chi^2(1) = 24.75$, $p < .001$.

Having demonstrated an association between mental simulation and uncertainty our next focus was on examining the temporal relationship between simulation and uncertainty in terms of changes in uncertainty over the three stages of simulations: initial representation, simulation run, and resulting representation. To pursue this analysis we first calculated the proportion of uncertainty segments in each stage to provide mean uncertainty scores for the initial representation, the simulation run, and the resulting representation. A paired-samples *t*-test revealed that initial representations had significantly higher uncertainty scores (Mean = 26%) than resulting representations (Mean = 15%), $t(125) = 2.58$, $p = .011$, two-tailed. Likewise, simulation runs had significantly higher uncertainty scores (Mean = 23%) than resulting representations (Mean = 15%), $t(124) = 2.43$, $p = .016$, two-tailed. Whilst the difference in uncertainty between initial representations and simulation runs was not reliable, $t(126) = 0.71$, $p = .48$, two-tailed, the essential pattern of results clearly indicates that mental simulations are serving to reduce uncertainty over time.

It is also worth noting that the baseline measure for uncertainty across all segments where simulation was absent was 13%. One-sample *t*-tests comparing

**Extract 10 E1, Analogising (bold typeface) occurring in association with mental simulation**

| | | |
|---|---|---|
| 1341 | Alan | is there is there an issue anyway erm guys with there being or having to be |
| 1342 | | or a benefit by having like a stand-by mode so it's either completely |
| 1343 | | switched o with or without the cap on it or there's like a stand-by mode |
| 1344 | | where it's sort of semi-warm but it's ready for action quickly |
| 1345 | Tommy | it has a home so a **docking station** |
| 1346 | Alan | yeah nice one |
| 1347 | Tommy | we could charge it in there as well plus it might be over budget but let's not |
| 1348 | | worry about that for now |
| 1349 | Alan | yeah so a docking station what would the docking station look like |
| 1350 | | (charge) |
| 1351 | Tommy | well it would just be a **cradle** it would just be somewhere for it to live |
| 1352 | | when you're not using it like a little protector |
| 1353 | | like an **inkwell** |
| 1354 | Alan | yeah |
| 1355 | Tod | [*laugh*] like a **quill** |
| 1356 | Rodney | a **quill** that means it's not something that you could put in your pencil case |

each simulation stage against this baseline revealed that both initial representations and simulation runs were significantly above baseline levels of uncertainty: $t(128) = 3.81$, $p < .001$, two-tailed, and $t(127) = 3.25$, $p = .002$, two-tailed, respectively. The difference between resulting representations and baseline uncertainty was not reliable, $t(126) = 0.72$, $p = .47$, two-tailed, suggesting that by the end of the simulation uncertainty had diminished to baseline levels. Overall, then, our analysis of the temporal associations between mental simulation and uncertainty replicated Christensen and Schunn's (in press-b) observations. Our data thus appear to validate the hypothesis that mental simulation is a strategic aspect of design cognition that functions to reduce epistemic uncertainty.

## 2.8 The association between mental simulation and analogising

One final issue of considerable interest concerns the possible existence of meaningful associations between mental simulation and analogising. To

**Table 6 The distribution of analogies as a function of their starting point within the three stages of mental simulations**

| | Analogical purpose | | |
|---|---|---|---|
| | *solution generation* | *explanation* | *function finding* |
| Initial representation | 16 | 4 | 9 |
| Simulation run | 3 | 4 | 3 |
| Resulting representation | 1 | 8 | 0 |

examine this issue we first determined whether any analogies were embedded or partly embedded within mental simulations in the sense that the analogies 'started' within some part of the simulation, whether in the initial representation, the simulation run, or the resulting representation. It transpired that 48 analogies showed a direct association with mental simulations (see Extract 10 for examples of analogising arising during mental simulation).

It was also possible to examine the way in which analogies having different 'purposes' were linked to mental simulations. Table 6 shows a breakdown of different types of analogies as a function of their actual starting point within the simulation. The distribution of analogies reveals some intriguing results. First, *solution-generation* and *function-finding* analogies appear early in the mental simulation, seemingly being 'generative' in nature (arguably producing novel variations that are explored in the subsequent run). Second, explanatory analogies tend to appear later in the mental simulation, seemingly arising in order to explain the simulation run or to explain the resulting representation.

It was not appropriate to apply a chi-square analysis to the data in Table 6 since 6 cells within the contingency table had expected counts of less than 5. We therefore combined the simulation run and resulting representation categories into a single 'late stage' category. A comparison of *solution-generation* analogies versus *explanation* analogies confirmed the contrasting distribution of these analogy types across the 'early' versus 'late' stages of the mental simulation process, $p < .002$, two-tailed, Fisher's Exact test. A similar comparison of *function finding* versus *explanation* analogies also confirmed the contrasting distribution of these analogy types across the early versus late stages of the mental simulation, $p < .02$, two-tailed, Fisher's Exact test.

# 3 General discussion

Our aim in this paper was to use the two engineering transcripts to pursue a detailed analysis of analogising and simulation strategies in design, with a close eye on the potential role of these strategies in dealing with the epistemic uncertainties that typically arise in design contexts (Schlosser and Paredis, 2007). Our previous research has indicated that epistemic uncertainty is critically related to:

- switches between breadth-first and depth-first modes of design development (Ball and Ormerod, 1995; Ball et al., 1997)
- strategic recourse to 'satisficing' heuristics in design evaluation (Ball et al., 1998)
- transitions from structural to functional modes of representation during the sketching of design objects (Kavakli et al., 1998; Scrivener et al., 2000)

In this study we wished to examine possible associations between epistemic uncertainty and strategies based around analogising and mental simulation.

Christensen and Schunn (in press-b) have already provided some compelling evidence that mental simulations are run under situations of subjective uncertainty to enable inferences that subsequently reduce such uncertainty. The DTRS7 dataset provided an excellent opportunity to validate this finding with a different design team working in a different design context and tackling a different engineering design task. Likewise, although previous research has informed our understanding of the nature of analogical reasoning in design (Christensen and Schunn, 2007; Ball et al., 2004; Casakin, 2004), we are not aware of studies that have attempted to draw links between analogising and epistemic uncertainty.

In terms of key findings, our analyses revealed that analogising and mental simulation are indeed intimately associated with situations of epistemic uncertainty in design. In the case of analogising, analogies were found to be temporally coupled with situations involving expressions of uncertainty, whereas pre-analogy and post-analogy segments revealed levels of uncertainty that were close to baseline values. Our interpretation of these observations is that analogical reasoning is a core design strategy that is instantiated *coincident* with situations of design uncertainty, serving to facilitate the *resolution* of such uncertainty. Turning to mental simulation, our analysis replicated Christensen and Schunn's (in press-b) findings and demonstrated that mental simulations arise concurrent with situations of uncertainty and, moreover, that levels of uncertainty dissipate to baseline values over the course of simulations. A further intriguing aspect of our analysis was that analogies were observed to interleave with mental simulations. Analogies within mental simulations that are aimed at solution generation and function finding appear to have a 'generative' role in design, whereby solution ideas are produced that are then explored and evaluated in subsequent simulation runs. On the other hand, explanatory analogies within mental simulations are mainly invoked to explain the nature of the simulation run or resulting representation; as such, they appear primarily in the later stages of mental simulations.

The existence of *function-finding* analogies in the present transcripts seems a unique observation that appears not to have been identified previously. We also note that these function-finding analogies were associated with a 'form-before-function' mode of design reasoning, with a single, extended episode of such reasoning being apparent in the transcripts. Form-before-function activity is rather different to the more typical 'function-before-form' reasoning seen in many design situations, and its occurrence is suggestive of some distinctive characteristics of the DTRS7 engineering design meetings (see Finke et al., 1992, for other evidence – as well as a cognitive model – of a form-before-function approach in creative invention and design). In particular, we propose that the focus of the meetings on brainstorming may have shifted the design team into a creatively rich phase of exploratory concept generation fuelled by function-finding analogies. It would be valuable to determine if this observation can be replicated in other brainstorming-oriented design meetings. Our analyses also permitted examination of the nature of simulation types and analogy types in design using previously identified categories (e.g. technical/functional versus end-user simulations, within-domain versus between-domain analogies, and problem identification versus solution-generation analogies). Our data here were broadly consistent with previous findings (Christensen and Schunn, 2007, in press-b) with discrepancies across studies being interpretable in terms of differences in the goals of the design teams (e.g., the brainstorming remit in the present context could account for the increase in between-domain analogies in comparison to the rates observed in earlier research).

By way of some final comments, we briefly reflect on how our examination of analogy, mental simulation and uncertainty in design relates to ideas presented by other researchers who have analysed the DTRS7 protocols. The analysis that relates most closely to our own is that undertaken by Stacey et al. (forthcoming), which discusses designers' references to *previous* design objects and the role that such references play in design thinking, including analogy-based design reasoning. These authors are critical of our own analogy-categorisation scheme (also used by Christensen and Schunn, 2007) that codes analogies in terms of 'purposes' such as problem identification, solution generation and explanation. We would argue, however, that our current analysis appears to validate this coding approach since we were readily able to categorise *all* design analogies with high levels of inter-coder reliability. Moreover, the way in which different analogy types were distributed across distinct phases of mental simulations attests to the sensitivity of the coding scheme to interesting nuances in design activity. We are also sceptical about Stacey et al.'s (forthcoming) attempt to extend an analogy coding scheme through the addition of new categories such as that of 'prepackaged analogies' (solution-generation analogies produced when designers are working alone that are then relayed within the meeting context). We suggest that describing solution-generation analogies as prepackaged adds a confusing *temporal* dimension to a purpose-oriented coding scheme. Prepackaged analogies are clearly *generative* in nature whether they arise prior to or during a meeting. At the same time, we note that Stacey et al.'s (forthcoming) focus on object references in design is far broader than ours, and we applaud their attempt to extend the analysis of prior object knowledge beyond concerns with analogical mapping. For example, we welcome their identification of object references that are used to set up contrast classes that define what a current design should *not* be like (what they term 'synthesis by exclusion'). We also value their observation that mappings from previous objects can *blend* in complex ways that suggest creative design ideas.

## 4 Conclusion

In conclusion, we believe that analysing the DTRS7 engineering transcripts for instances of analogising, mental simulation and uncertainty has provided valuable insights into central aspects of processing in innovative design contexts. In particular, we have replicated and extended previous findings linking epistemic uncertainty to key design strategies. In addition, we have been alerted to novel issues that will be important to examine in the future, such as the role of function-finding analogies as a dominant aspect of form-before-function reasoning in creative design.

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## References

**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* Vol 3 No 4 pp 247–270

**Ball, L J, Maskill, L and Ormerod, T C** (1998) Satisficing in engineering design: causes, consequences and implications for design support, *Automation in Construction* Vol 7 No 2/3 pp 213–227

**Ball, L J and Ormerod, T C** (1995) Structured and opportunistic processing in design: a critical discussion, *International Journal of Human-Computer Studies* Vol 43 No 1 pp 131–151

**Ball, L J, Ormerod, T C and Morley, N J** (2004) Spontaneous analogising in engineering design: a comparative analysis of experts and novices, *Design Studies* Vol 25 No 5 pp 495–508

**Bearman, C R, Ball, L J and Ormerod, T C** (2007) The structure and function of spontaneous analogising in domain-based problem solving, *Thinking and Reasoning* Vol 13 No 3 pp 273–294

**Casakin, H** (2004) Visual analogy as a cognitive strategy in the design process: expert versus novice performance, *Journal of Design Research* Vol 4 No 2

**Casakin, H and Goldschmidt, G** (1999) Expertise and the visual use of analogy: implications for design education, *Design Studies* Vol 20 No 2 pp 153–175

**Christensen, B T and Schunn, C D** (2007) The relationship of analogical distance to analogical function and pre-inventive structure: the case of engineering design, *Memory and Cognition* Vol 35 No 1 pp 29–38

**Christensen, B T and Schunn, C D** 'Putting blinkers on a blind man': providing cognitive support for creative processes with environmental cues, in **K Wood and A B Markman** (eds) *Tools for innovation*, Oxford University Press, Oxford (in press-a)

**Christensen, B T and Schunn, C D** The role and impact of mental simulation in design, *Applied Cognitive Psychology* (in press-b)

**Dahl, D W and Moreau, P** (2002) The influence and value of analogical thinking during new product ideation, *Journal of Marketing Research* Vol 39 No 1 pp 47–60

**Davidson, J E, Deuser, R and Sternberg, R J** (1996) The role of metacognition in problem solving in **J Metcalfe and A P Shimamura** (eds) *Metacognition: knowing about knowing*, MIT Press, Cambridge, MA pp 207–226

**Dunbar, K and Blanchette, I** (2001) The *in vivo/in vitro* approach to cognition: the case of analogy, *Trends in Cognitive Sciences* Vol 5 No 8 pp 334–339

**Finke, R, Ward, T B and Smith, S M** (1992) *Creative cognition: theory, research, and applications* MIT Press, Cambridge, MA

**Forbus, K D** (1997) Qualitative reasoning in **A B Tucker** (ed) *CRC handbook of computer science and engineering*, CRC Press pp 715–733

**Gentner, D** (2002) Psychology of mental models in **N J Smelser and P B Bates** (eds) *International encyclopedia of the social and behavioral sciences*, Elsevier, Amsterdam pp 9683–9687
**Gentner D and Stevens A L** (eds) (1983) *Mental models*, Erlbaum, Hillsdale, NJ
**Hegarty, M and Just, M A** (1993) Constructing mental models of machines from text and diagrams, *Journal of Memory and Language* Vol 32 No 6 pp 717–742
**Hegarty, M, Kriz, S and Cate, C** (2003) The role of mental animations and external animations in understanding mechanical systems, *Cognition and Instruction* Vol 21 No 4 pp 325–360
**Holyoak, K J and Thagard, P** (1995) *Mental leaps: analogy in creative thought* MIT Press, Cambridge, MA
**Kavakli, M, Scrivener, S A R and Ball, L J** (1998) Structure in idea-sketching behaviour, *Design Studies* Vol 19 No 4 pp 485–518
**Nersessian, N J** (2002) The cognitive basis of model-based reasoning in science in **P Carruthers and S Stich** (eds) *Cognitive basis of science*, Cambridge University Press, New York pp 133–153
**Quayle, J D and Ball, L J** (2000) Working memory, metacognitive uncertainty, and belief bias in syllogistic reasoning, *Quarterly Journal of Experimental Psychology* Vol 53A No 4 pp 1202–1223
**Schank, R C** (1999) *Dynamic memory revisited* Cambridge University Press, Cambridge, UK
**Schlosser, J and Paredis, C J J** (2007) *Managing multiple sources of epistemic uncertainty in engineering decision making* Paper presented at the SAE World Congress and Exhibition, Detroit, MI, USA, April 2007
**Schwartz, D L and Black, J B** (1996) Analog imagery in mental model reasoning: depictive models, *Cognitive Psychology* Vol 30 No 2 pp 154–219
**Scrivener, S A R, Ball, L J and Tseng, W S -W** (2000) Uncertainty and sketching behaviour, *Design Studies* Vol 21 No 5 pp 465–481
**Stacey, M, Eckert, C and Earl, C** From Ronchamp by sledge: on the pragmatics of object references, in **J McDonnell and P Lloyd** (eds) *About: designing - analysing design meetings*, Taylor and Francis, UK (forthcoming)
**Tafel, E** (1979) *Years with Frank Lloyd Wright: apprentice to genius* Dover Publications, New York
**Trickett, S B and Trafton, J G** (2002) The instantiation and use of conceptual simulations in evaluating hypotheses: movies-in-the-mind in scientific reasoning in *Proceedings of the 24th annual conference of the cognitive science society*, Erlbaum, Mahwah, NJ pp 878–883
**Trickett, S B, Trafton, J G, Saner, L and Schunn, C D** (2005) 'I don't know what's going on there': the use of spatial transformations to deal with and resolve uncertainty in complex visualizations in **M C Lovett and P Shah** (eds) *Thinking with data*, Erlbaum, Mahwah, NJ pp 65–86
**Visser, W** (1996) Use of episodic knowledge and information in design problem solving in **N Cross**, **H Christiaans and K Dorst** (eds) *Analysing design activity*, Wiley, Chichester, UK pp 271–289