The structure of concurrent cognitive actions: a case study on novice and expert designers

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This paper presents a case study of concurrent cognitive actions of a novice and an expert designer. We analyzed cognitive actions of designers using the retrospective protocol analysis method and found evidence of the coexistence of certain types of cognitive action in both novices' and expert designers' protocols. The main difference between the two designers' protocols is the structure of concurrent cognitive actions. While the expert's cognitive actions are clearly organized and structured, there are many concurrent actions that are hard to categorize in the novice's protocol. We also found that the expert's cognitive activity and productivity in the design process were three times as high as the novice's. The results from this single case study raise a question for further studies: do structured and organized acts govern performance in the design process?

Keywords: design cognition, design strategy, information processing, conceptual design, case study

Results of analysis of design protocols of a novice and an expert designer have shown that although there is no clear evidence for causality among cognitive actions, there is evidence for the coexistence of the cognitive actions[1,2]. Certain groups of cognitive actions increase and decrease in parallel with each other in the protocols of the novice and the expert designer. We also found supporting evidence from Finke *et al*[3] and Kosslyn[4], based on the coexistence of different types of cognitive actions in creative processes. In creative cognition, there are usually many kinds of cognitive process operating conjunctively and at varying rates[3]. In the mental imagery experiments conducted by Kosslyn *et al*[5], there was also a wide range of correlations in the performance of the tasks.

1 **Suwa, M, Gero, J S and Purcell, T** 'How an architect created design requirements' in G and W (eds), *Design Thinking Research Symposium: Design representation* II, MIT Press, Cambridge, MA (1999) pp 101–124
2 **Kavakli, M and Gero, J S** 'Sketching as mental imagery processing' *Design Studies* Vol 22 No 4 (2001) 347–364
3 **Finke, R A, Ward, T B and Smith, S M** *Creative cognition, theory, research, and applications* MIT Press, Cambridge, MA (1992)
4 **Kosslyn, S M** *Image and brain: the resolution of the imagery debate* MIT Press, Cambridge, MA (1994)

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0142-694X/02 $ - see front matter *Design Studies* **23** (2002) 25–40
PII: S0142-694X(01)00021-7

In this paper, we investigate the concurrent actions using design protocols by means of the correlations between them. Our objective is to explore the structure of the concurrent cognitive actions in the expert's and novice designer's protocols, and to discuss the differences in performance by showing the differences in the structure of cognitive processes. Because of the limited number of designers analysed in this research study, we do not intend to draw general conclusions from the experimental results. We assume sketching in conceptual design is a form of mental imagery processing[2]. Many of the brain areas that are activated when we recognize and identify objects are also activated during visual mental imagery[4]. Mental imagery processing consists of image generation (drawing production), inspection (attention), transformation (reinterpretation) and information retrieval from a case base in long-term memory. Eventually, all of these processes affect the rate of cognitive activity. Kosslyn *et al*[5] found a wide range of correlations in the performance of the tasks. They stated that different aspects of imagery are accomplished by using separate subsystems, which are invoked in different combinations in different tasks. A person who is poor at one process (because one or more necessary subsystems are ineffective) will be poor at all tasks that require it—but not necessarily poor at tasks that do not require it. According to Kosslyn[6], imagery ability is not all-or-none; a given person is not generally good or bad at imagery. If imagery ability was a single trait, then those who did well on one task should have done well on all the others.

We found that the expert's cognitive activity and productivity (in terms of image generation) were three times as high as the novice's in the overall design process[7]. However, the novice's performance in certain types of task (such as discovery of implicit spaces) was higher than the expert's. How can we explain this? Adopting Kosslyn's explanation, this would make sense if different aspects of imagery are accomplished by using separate subsystems. By taking it one step further, we look for its reason in the structure of concurrent cognitive actions. Is there a difference in the structure of cognitive actions between the novice's and expert designer's protocols? If so, there may be a correlation between the structure of concurrent cognitive actions and the performance of designers.

1 Codes of cognitive actions

We used the content-oriented retrospective protocol analysis method to investigate concurrent cognitive actions of designers. Suwa and Tversky[8] classified the contents of what designers see, attend to, and think of into four information categories: depicted elements and their perceptual features, spatial relations, functional thoughts, and knowledge. The first two

5 **Kosslyn, S M, Brunn, J, Cave, K R and Wallach, R W** 'Individual differences in mental imagery ability: a computational analysis' *Cognition* Vol 18 (1984) 195–243

6 **Kosslyn, S M** 'Mental imagery' in **S M Kosslyn and D N Osherson** (eds) *An invitation to cognitive science*, 2nd ed., *Visual cognition* 2, MIT Press, Cambridge, MA (1995) pp 267–296

7 **Kavakli, M, Suwa, M, Gero, J S and Purcell, T** 'Sketching interpretation in novice and expert designers' in **J S Gero and B Tversky** (eds) *Visual and spatial reasoning in design*, Key Centre of Design Computing and Cognition, University of Sydney, Sydney (1999) pp 209–219

8 **Suwa, M and Tversky, B** 'What architects see in their design sketches: implications for design tools' in *Human factors in computing systems: CHI'96*, ACM, New York (1996) pp 191–192

Table 1 Codes of D-actions and M-actions in the category of physical actions

D-actions: drawing actions	*M-actions: moves*
Dc: create a new depiction	Moa: motion over an area
Drf: revise an old depiction	Mod: motion over a depiction
Dts: trace over the sketch	Mrf: move attending to relations or features
Dtd: trace over the sketch on a different sheet	Ma: move a sketch against the sheet beneath
Dsy: depict a symbol	Mut: motion to use tools
Dwo: write words	Mge: hand gestures

give us visual information, while the latter two give us non-visual information. The design protocols were collected as a retrospective report after the design session. These protocols were divided into segments, indexed and coded according to these information categories. Information on procedures of protocol parsing and coding can be found in Suwa *et al*[9,10]. In the coding scheme, different modes of a designer's cognitive actions are coded for each segment. There are four modes of cognitive actions in this version of the coding scheme[9]: physical, perceptual, functional and conceptual. Tables 1–4 show the subcategories and codes of the cognitive actions we used to analyze the design protocols.

2 *Differences in cognitive activity and productivity*

Using the coding scheme developed by Suwa *et al*[9], we analyzed the cognitive processes of a novice and an expert designer. In the protocols, the novice is a second-year student of architecture and the expert is a practising architect with more than 25 years' experience. The purpose of the analysis was not to obtain results with complete generality but to assess whether this type of approach could produce useful results and whether there were indicative differences.

Table 2 Codes of P-actions

P-actions: perceptual actions related to implicit spaces	*P-actions: perceptual actions related to features*	*P-actions: perceptual actions related to relations*
Psg: discover a space as a ground	Pfn: attend to the feature of a new depiction	Prn: create or attend to a new relation
Posg: discover an old space as a ground	Pof: attend to an old feature of a depiction	Prp: discover a spatial or organizational relation
	Pfp: discover a new feature of a new depiction	Por: mention or revisit a relation

9 **Suwa, M, Gero, J S and Purcell, T** 'Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions' *Design Studies* Vol 19 No 4 (1998) 455–483

10 **Suwa, M, Gero, J S and Purcell, T** 'Analysis of cognitive processes of a designer as the foundation for support tools' in **J S Gero and F Sudweeks** (eds) *Artificial Intelligence in Design'98*, Kluwer, Dordrecht (1998) pp 229–248

Table 3 Codes of F-actions

F-actions: functional actions related to new functions	*F-actions: functional actions related to revisited functions*	*F-actions: functional actions related to implementation*
Fn: associate a new depiction, feature or relation with a new function	Fo: continuing or revisited thought of a function	Fi: implementation of a previous concept in a new setting
Frei: reinterpretation of a function	Fop: revisited thought independent of depictions	
Fnp: conceiving of a new meaning independent of depictions		

Table 4 Codes of G-actions

G-actions: goals	*Subcategories of G1 type goals*
G1: goals to introduce new functions	G1.1: based on the initial requirements
G2: goals to resolve problematic conflicts	G1.2: directed by the use of explicit knowledge or past cases (strategies)
G3: goals to apply introduced functions or arrangements in the current context	G1.3: extended from a previous goal
G4: repeated goals from a previous segment	G1.4: not supported by knowledge, given requirements or a previous goal

The first step of the coding process is segmentation. A cognitive segment consists of cognitive actions that appear to occur simultaneously. We found that the design protocol of the expert includes 2916 actions and 348 segments, while the novice's protocol includes 1027 actions and 122 segments. In both protocols, each segment includes eight cognitive actions on average. However, considering that the same amount of time was given to both participants, the expert's design protocol is 2.8 times as rich as the novice's in terms of actions. There were also 2.8 times as many segments in the expert designer's session as in the novice's.

During the design process, the expert produced 13 pages of sketches including seven different alternatives, while the novice produced four pages including two alternatives. Figures 1 and 2 show samples of the sketches produced by both the novice and the expert. We do not analyze the sketches themselves in this paper; they are presented simply to ground the following work.

Based on these results, we can claim that the expert is more active and productive than the novice in the conceptual design process, but why?

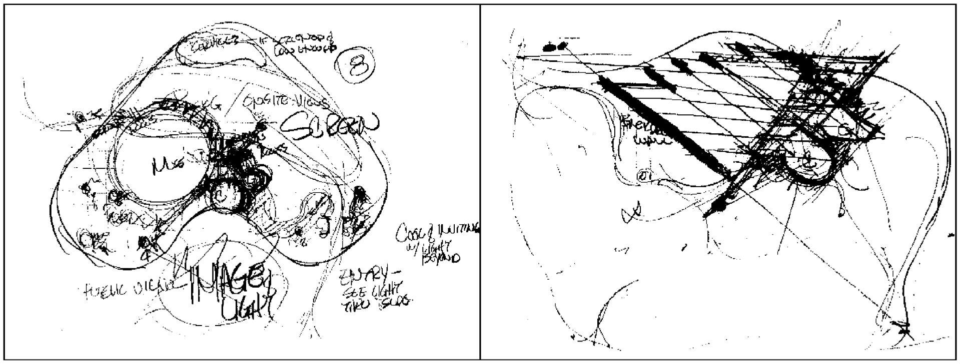

Figure 1 Samples from the sketches of the expert

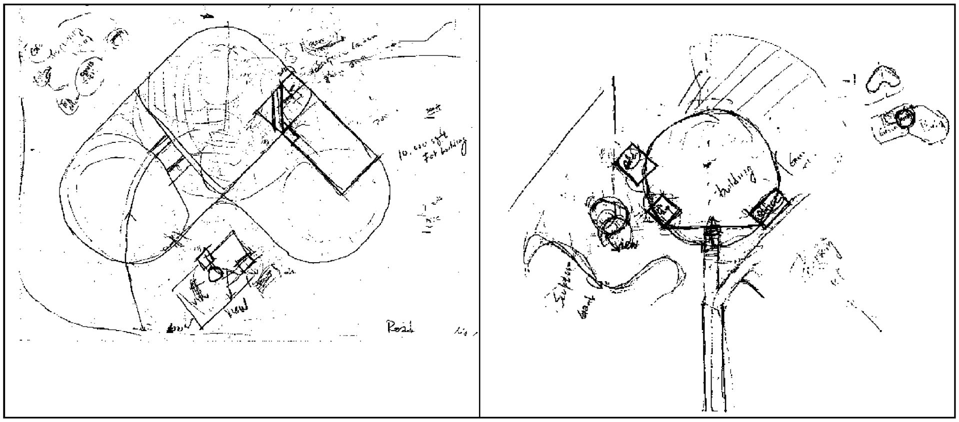

Figure 2 Samples from the sketches of the novice

Could the differences in the structure of concurrent cognitive actions cause the difference in performance?

3 *Concurrent cognitive actions*

Our experimental results show that although the novice's cognitive activity started at a peak, it dropped continuously until the end of the design session; whereas the expert's cognitive activity rose continuously during the design session. Kosslyn[6] asserted that 'Several mechanisms working together could generate images, and these mechanisms may have other roles as well. By analogy, a car can slow down if one simply takes one's foot off the gas, which does not activate a separate *slowing-down* system'. Adopting Kosslyn's approach, we can state that if the cognitive activities slow down at some stage, this may be because of not only one activity, but also other activities having different roles that occur together. There-

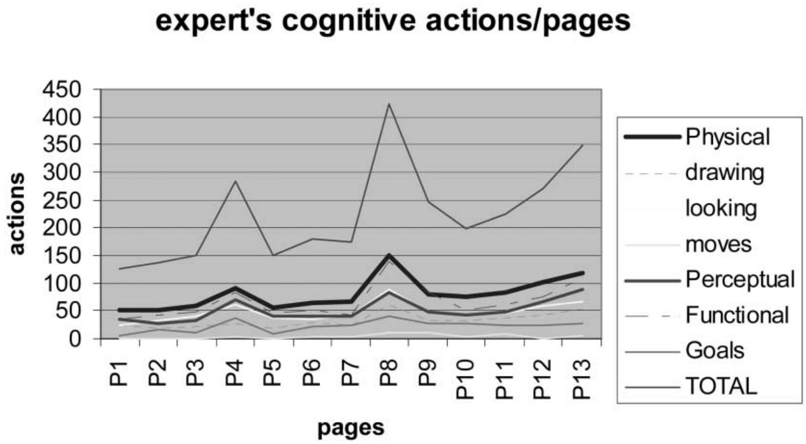

Figure 3 Expert's cognitive activity

fore, we could look for its reason in concurrent cognitive actions, rather than only within a certain group of cognitive actions.

We analyzed the rates of cognitive segments and actions on pages produced, and found the rates of cognitive actions and segments in both design protocols are strongly correlated with each other (0.94 for the expert and 0.92 for the novice). Since our purpose is to explore concurrent cognitive processes, we investigated the cognitive actions in pages that indicate strong correlations in both design protocols. As shown in Figures 3 and 4, the cognitive activity of designers appears to be parallel to the drawing production on pages in both design protocols. This shows that cognitive

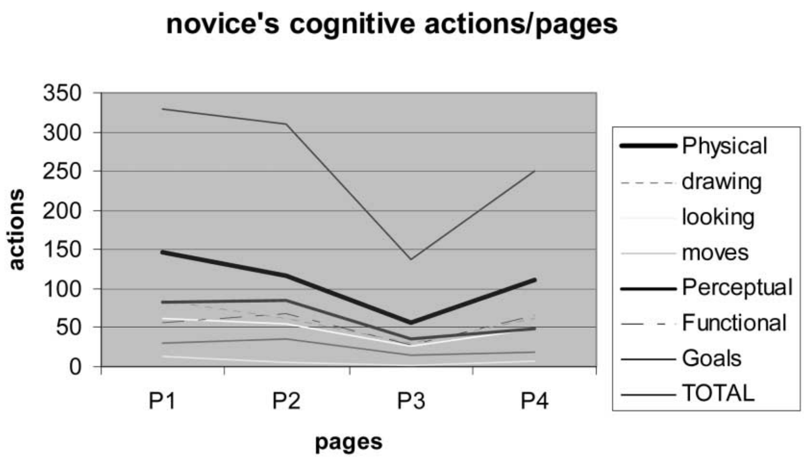

Figure 4 Novice's cognitive activity

actions including looking, perceptual and functional actions, as well as certain types of goals, increase and decrease in parallel with each other in both protocols.

As can be seen in Table 5, there are strong correlations between different types of cognitive action in pages in both design protocols.

Drawing actions are strongly correlated with looking actions (0.864 for the expert and 0.968 for the novice) and moves (0.975 for the expert and 0.951 for the novice) in both design protocols. In addition to this, for the expert, drawing actions are also strongly correlated with perceptual actions (0.998), functional actions (0.998) and goals (0.995). However, for the novice, correlations of drawing actions with perceptual actions (0.786) and functional actions (0.744) are not as strong as the expert's, and drawing actions are weakly correlated with goals (0.665). In both design protocols, a strong correlation is seen between perceptual actions and goals (0.996 for the expert and 0.981 for the novice). In the expert's design protocol, there are also very strong correlations between functional actions and perceptual actions (0.998), and functional actions and goals (0.996), while they are weakly correlated in the novice's (0.670 and 0.617).

4 *Concurrent cognitive processing*

We now investigate the correlations between subcategories of cognitive actions. In this paper, we focus on only the concurrent actions highly correlated with depicting drawings. We categorize the concurrent actions into two groups: primary concurrent actions and secondary concurrent actions.

Table 5 Correlation coefficients of cognitive actions in pages

	Drawing	*Looking*	*Perceptual*	*Functional*	*Goals*	*Moves*
expert-page						
Drawing	1.000					
Looking	0.864	1.000				
Perceptual	0.998	0.909	1.000			
Functional	0.998	0.951	0.998	1.000		
Goals	0.995	0.829	0.996	0.996	1.000	
Moves	0.975	0.635	0.968	0.978	0.975	1.000
novice-page						
Drawing	1.000					
Looking	0.968	1.000				
Perceptual	0.786	0.898	1.000			
Functional	0.744	0.828	0.670	1.000		
Goals	0.655	0.806	0.981	0.617	1.000	
Moves	0.951	0.862	0.680	0.504	0.529	1.000

Primary concurrent actions are the cognitive actions that correlate directly with depicting drawings. Secondary concurrent actions are the cognitive actions that correlate highly with the primary actions. Table 6 lists the primary concurrent actions with depicting drawings.

In this and the following tables, '+' refers to positive strong correlations and '−' to negative strong correlations, while '~' refers to substantial correlations among cognitive actions and '0' refers to the cognitive actions that do not correlate. The actions in bold face highlight significant differences between the novice and expert designers.

As we can see in Table 6, strong correlations in both design protocols are seen between depicting drawings (Dc) and looking actions (L), discovery of a relation (Prp), and association of a new depiction with a function (Fn). In addition to these, creation of a new relation (Prn) and revisited thought of a function (Fo) have also strong correlations with depicting drawings

Table 6 Primary concurrent actions correlated with depicting drawings (Dc) (+, strong positive correlation; −, strong negative correlation; ~, substantial correlation; 0, weak/no correlation)

Action code	*Novice*	*Expert*	*Cognitive action*
L	+	+	Looking at old depictions
Dts	+	~	Overtracing
Por	+	~	Mention of a relation
Prp	+	+	Discovery of a spatial or an organizational relation
Prn	0	+	**Creation of a new relation**
Fo	~	+	Continual or revisited thought of a function
Fn	+	+	Association of a new depiction with a function
Moa	+	~	Motion over an area
G1.2	+	~	Goals directed by the use of explicit knowledge or past cases
Dwo	+	0	**Writing**
Dsy	+	0	**Depicting symbols**
Dtd	−	0	**Tracing over the sketch on a different sheet**
Psg	+	0	**Discovery of a new space as a ground**
Pfp	+	0	**Discovery of a new feature of a new depiction**
G1-4	+	0	**Goals not supported by knowledge, requirements or goals**
G3	+	0	**Goals to apply introduced functions in the current context**

(Dc) in the expert's design protocol, while there are weak correlations in these categories in the novice's design protocol.

However, except for these two (Prn and Fo), there are many actions that occur together in the novice's protocol in parallel to depicting drawings. Concurrent actions in the novice's design protocol are overtracing (Dts), writing (Dwo), depicting symbols (Dsy), discovery of a space as a ground (Psg), discovery of a new feature of a new depiction (Pfp), mention of a relation (Por), motion over an area (Moa), goals directed by the use of explicit knowledge or past cases (G1-2), goals not supported by knowledge, requirements or previous goals (G1-4), and goals to apply previously introduced functions in the current context (G3). Tracing over the sketch on a different sheet (Dtd) is also strongly negative correlated with depicting drawings (Dc) for the novice. On the contrary, discovery of a new space as a ground (Psg) is, surprisingly, negative (though weakly) correlated for the expert.

Table 7 lists secondary concurrent actions (that occur parallel to the primary concurrent actions). The first column indicates the primary concurrent action code, which is parallel to depicting drawings. The second column indicates its correlation value with depicting drawings in the novice's design protocol, while the third indicates the same in the expert's. Secondary concurrent actions listed in a row are the ones correlated strongly with the primary concurrent action in the first column. We can see in Table 7 that many concurrent cognitive actions coexist in the novice's design protocol, while only a small group of cognitive actions occurs in parallel in the expert's.

Table 8 is the classification of the secondary concurrent actions into groups. For example, looking actions (L) correlate highly with depicting drawings (Dc) in both design protocols as shown in the second and third columns in Table 8. The fourth and fifth columns indicate the cognitive actions that correlate highly with this particular group of actions. In the expert's design protocol, as implied by the fifth column, looking actions (L) correlate highly with a group of actions including depicting drawings (Dc), discovery of a relation (Prp), mention of a relation (Por), and revisited thought of a function (Fo). The same group can be seen in the novice's design protocol, as shown in the fourth column, but there is a member of this particular group missing in the novice's design protocol. Since this list of actions appears in at least one of the expert's or novice's design protocols among the concurrent actions, we call this list of actions (including the action code in the first column) a group and label it Group A in Table 8. Group C is another example of this type of grouping. It consists of a group

Table 7 Secondary concurrent actions correlated with depicting drawings (Dc) (+, positive strong correlation; −, negative strong correlation; ~, substantial correlation; 0, weak/no correlation)

Action code	*Novice*	*Expert*	*Novice's secondary concurrent actions*	*Expert's secondary concurrent actions*
L	+	+	Dc, Dts, −Dtd, Dwo, Psg, Posg, Pfp, Prp, Por, Fn, G1-2, G1-4, G3, Moa	Dc, Prp, Por, Fo
Dts	+	~	Dc, Pfn, −Prn, Fi, G1-1, Ma	Dtd
Por	+	~	Dc, Dts, −Dtd, Dwo, L, Posg, Prp, Fo, G1-2, G1-4, G2, G3	L, Prp, Fo
Prp	+	+	Dc, Dts, −Dtd, Dwo, L, Psg, Posg, Pfp, Por, Fn, G1-2, G1-4, G3, Moa	Dc, L, Pof, Por, Fo
Prn	0	+		Dc
Fo	~	+	−Dtd, Pfn, Por, Frei, Fop, G1-3, G1-4, G2, G3	Dc, L, Prp, Por
Fn	+	+	Dc, Dsy, L, Psg, Pfp, Prp, −Pof	Dc
Moa	+	~	Dc, Dts, Dsy, L, Psg, Pfp, Prp, Fn, Fnp, Mod	Dc, Fn, Fop, G1-2
G1.2	+	~	Dc, Dts, Dwo, L, Psg, Posg, Prp, Prn, Por, −G1.1, G1.4, G4, −Ma	Moa
Dwo	+	0	Dc, Dts, L, Posg, Prp, Prn, Por, G1-2, G1-4, G2, G3	
Dsy	+	0	Dc, Psg, Pfp, −Pof, Fn, Fnp, Mod, Moa	
Dtd	−	0	−Dc, −Dts, −L, −Pfn, −Prp, −Por, −Fo, −Fi, −G1-4, −G3	
Psg	+	0	Dc, Dts, Dsy, L, Pfp, Prp, Fn, Fnp, −G1.1, G1-2, G4, −Ma, Mod, Moa	
Pfp	+	0	Dc, Dts, Dsy, L, Psg, Fo, Fi, G3	
G1-4	+	0	Dc, Dts, −Dtd, Dwo, L, Posg, Prp, Por, Fo, G1-2, G2, G3	
G3	+	0	Dc, Dts, −Dtd, Dwo, L, Posg, Pfn, Prp, Por, Frei, Fo, Fop, G1-3, G1-4, G2	

of actions taking place as a full list in both design protocols. It includes the association of a new depiction with a function (Fn), goals directed by the use of explicit knowledge or past cases (G1-2), and motion over an area (Moa). Similar to Group A, Group C also appears with a missing member in some other categories in both design protocols. The other groups (B, D, E, F, H, J, K) are produced with the same criteria of appearing at least once as a full group among concurrent actions. Groups in which all the members are negative are represented by a − prefix. We represent the missing members in a group with a − followed by the number missing and the group member itself in parentheses {}, for example, A−1{Fo} means group A less one member, Fo.

Table 8 Grouped secondary concurrent actions correlated with depicting drawings (Dc) (+, strong positive correlation; −, strong negative correlation; ~, substantial correlation; 0, weak/no correlation)

Action code	*Novice's Dc correlation*	*Expert's Dc correlation*	*Novice's secondary concurrent action*	*Expert's secondary concurrent action*
L	+	+	**A−1** {Fo}, **B**, **C**, **D**	**A**
Dts	+	~	**G**, **−J−1**{G4}, Dc	Dtd
Por	+	~	**A**, **B**, **D−2**{Psg, Pfp}, **E**	**A−1**{Dc}
Prp	+	+	**A−1** {Fo}, **B**, **C**, **D**	**A**, Pof
Prn	0	+		Dc
Fo	~	+	**B−1**{Dwo}, **H**, Por	**A**
Fn	+	+	**A−2**{Por, Fo}, **D−2**{Dts, Posg}, **F**	Dc
Moa	+	~	**A−2**{Por, Fo}, **D−1**{Posg}, **F−1**{−Pof}, **K**	Dc, Fop, **C**
G1.2	+	~	**A−1** {Fo}, **D−1**{Pfp}, **J**, Dwo, G1.4	**C−1**{Fn}
Dwo	+	0	**A−1** {Fo}, **B−1**{−Dtd}, **D−2**{Psg, Pfp}, **E**, Prn	
Dsy	+	0	**D−2**{Dts, Posg}, Dc, **F**, **K**, Moa	
Dtd	−	0	**−A**, −Dts, **−G**, −G1-4, −G3	
Psg	+	0	**A−2**{Por, Fo}, **C**, **D−1**{Posg}, **J−1**{Prn}, **K**, Dsy	
Pfp	+	0	**A−2**{Por, Prp}, **D−1**{Posg}, Dsy, Fi, G3	
G1-4	+	0	**A**, **B**, **D−2**{Psg, Pfp}, **E**	
G3	+	0	**A**, **B**, **D−2**{Psg, Pfp}, **H**	

Group A={Dc, L, Prp, Por, Fo}; Group B={−Dtd, Dwo, G1-4, G3}; Group C={Fn, G1-2, Moa}; Group D={Dts, Posg, Psg, Pfp}; Group E={G1-2, G2}; Group F={Dsy, −Pof, Fn}; Group G={Pfn, Fi}; Group H={Pfn, Frei, Fop, G1-3, G2}; Group J={Prn, −G1-1, G4, −Ma}; Group K={Fnp, Mod}.
X—*n* {*w*, *z*}: *X*—group code; −*n*—number of missing group members; {*w*, *z*}—missing members.

As we can see in Table 8, the expert's secondary cognitive actions are more structured in comparison to the novice's cognitive actions, while there are many concurrent actions in the novice's design protocol. In the expert's protocol, strong correlations can be seen in the coexistence of only one group of secondary concurrent actions. It is either A including depicting drawings (Dc), looking actions (L), discovery of a relation (Prp), mention of a relation (Por) and revisited functions (Fo), or C including association of a new depiction with a function (Fn), goals directed by the use of explicit knowledge or past cases (G1-2) and motion over an area (Moa). Whereas, in the novice's protocol, cognitive performance has been divided into many groups of actions—B, C, D, E, F, G, H, J, K—in addition to A. The novice's secondary concurrent actions appear to be combinations of these groups of actions.

Thus, Table 8 indicates that the expert's cognitive activity is based on the coexistence of limited number of actions (5+1 at most) for each primary concurrent action code. However, in the novice's protocol secondary concurrent actions range from 7 to 16, which is more than the human short-term memory can manage at one time[11].

5 *Structure in cognitive activity*

In this case study, we found evidence for a clear structural organization in the expert's concurrent cognitive actions. If we categorize our findings in a hierarchical order, at the higher level we found a structural interdependency between the categories of cognitive actions in the expert's design protocol. This structural interdependency might be a reason for his high performance in the design process. In the expert's design protocol, there are strong correlations between:

- drawing actions, perceptual actions, functional actions, goals and moves (while they do not correlate with each other as strongly in the novice's protocol as in the expert's),
- functional actions and perceptual actions,
- functional actions and goals,
- drawing actions and goals (while they are weakly correlated in the novice's protocol), and
- moves, perceptual actions, functional actions and goals (while they are not correlated in the novice's protocol).

This interdependency at a higher level is the first clue for a top-down structural organization in the expert's design protocol. At lower levels, drawing actions in the expert's design protocol do not correlate with each other (except for overtracing and copying drawings). However, there are many correlations in the novice's design protocol among:

- drawing actions and
- functional actions.

According to our experimental findings, there are concurrent cognitive actions in both design protocols and the cognitive activities of the designers in certain categories seem to be parallel to the drawing production on the pages they produced. In the first step, when we investigated the correlations between depicting drawings and other cognitive actions, we found a coexistence of four primary actions in both design protocols:

- depicting drawings,
- looking actions,
- association of a new depiction with a function, and
- discovery of a relation.

In addition to these, in the expert's design protocol, there are two more

11 **Miller, G A** 'The magical number seven, plus or minus two: some limits on our capacity for processing information' *Psychological Review* Vol 63 (1956) 81–97 primary actions that coexist with depicting drawings which indicate weak correlations in the novice's design protocol:

- creation of a new relation and
- revisited thought of a function.

Their coexistence in the expert's cognitive activity might be attributed to the higher rates in his performance.

We also found many actions that occur together in the novice's protocol in parallel to depicting drawings. In addition to the four actions listed above, there are 11 primary actions that coexist with depicting drawings:

- overtracing,
- writing,
- depicting symbols,
- discovery of a space as a ground,
- discovery of a new feature of a new depiction,
- mention of a relation,
- motion over an area,
- goals directed by the use of explicit knowledge or past cases,
- goals not supported by knowledge, requirements or previous goals,
- goals to apply previously introduced functions in the current context, and
- tracing over the sketch on a different sheet (strongly negative correlated).

When we investigated the correlations between drawing depictions and secondary concurrent cognitive actions, we also found that, in the expert's protocol, strong correlations are seen in the coexistence of only one group of actions (either A or C). Whereas, in the novice's protocol, cognitive performance is divided into 10 groups of actions—B, C, D, E, F, G, H, J, K—in addition to A. Group A, mostly seen in both protocols, includes the following cognitive actions:

- depicting drawings,
- looking actions,
- discovery of a relation,
- mention of a relation and
- revisited functions.

Group C, which is another group of actions seen in both protocols, includes the following actions:

- association of a new depiction with a function,
- goals directed by the use of explicit knowledge or past cases, and

• motion over an area.

In Table 8, we see only two more secondary cognitive actions (mention of a relation and visited actions) that join the four-member list of primary actions. The expert's cognitive activity is based on the coexistence of six actions, which is between the limits of human short-term memory (+7 or −2). However, in the novice's protocol, 14 primary cognitive actions coexist with seven to 16 secondary concurrent actions, which is beyond the capacity of human short-term memory.

With this limited evidence, we propose that the difference in performance in the design process may be attributed to the difference in structure of concurrent cognitive actions. This case study indicates that the expert's cognitive actions are more structured and organized in comparison with the novice's cognitive actions.

Another interesting finding is the evidence of a systematic expansion in the expert's goals. In the expert's design protocol, we found strong correlations between the goals extended from a previous goal and

- the goals to apply previously introduced functions, and
- repeated goals from a previous segment.

In the novice's protocol, there is no such correlation: the goals extended from a previous goal correlate strongly with the goals to resolve problematic conflicts. We also found evidence for a similar systematic expansion in the experts' design protocols in the experimental findings of Adelson and Soloway[12].

In addition to these, we also found evidence for an exhaustive search in the novice's design protocol, which may also contribute to the difference in performance. As pointed out by Granovskaya *et al*[13], the process of amalgamating a new basis for classification (allowing one to reduce exhaustive search when choosing a strategy for solving a problem) involves changes in an alphabet of motion components. The changes result in the complete disappearance of external movements and formation of structures, which replace motions in analysis. Once these structures are present, the recognition process rate is increased so much that it gives the impression of being an insight.

While the structure of concurrent cognitive actions is a reasonable explanation for the increasing cognitive activity in the expert's design protocol, it may also bring an explanation for the higher rates of certain type of

12 Adelson, B and Soloway, E 'The role of domain experience in software design' in **B Curtis** (ed.) *Human factors in software development*, IEEE Computer Society Press, Washington, DC (1985) pp 233–242
13 Granovskaya, R M, Bereznaya, I Y and Grigorieva, A N *Perception of form and forms of perception* Lawrence Erlbaum, London (1987)

discovery in the novice's cognitive activity. We found that in the novice's protocol depicting drawings correlates strongly with:

- discovery of a space as a ground,
- discovery of a new feature and
- discovery of a spatial or organizational relation

(while it does not correlate with any other perceptual actions in the expert's). In the expert's protocol discovery of a new space as a ground is negatively (though weakly) correlated with depicting drawings. This might be a reason for the expert's lower rates of discoveries in this category.

6 *Structure in cognitive activity*

In this case study, we analyzed the rates of cognitive segments and actions on pages produced and, then, investigated the correlations between them. As a result, we have found evidence of the coexistence of certain types of cognitive action in cognitive processes. We have also found clues for structural organization and systematic expansion in the expert's cognitive activity as opposed to the exhaustive search in the novice's. There is a considerable difference in the speed and rate of cognitive actions. The speed of the cognitive processes in the expert's design protocol is much higher, and the rate of the cognitive segments and actions in the expert's design protocol increases on pages produced, while the novice's cognitive actions decrease. We have provided evidence that many cognitive actions coexist in the novice's design protocol in parallel to depicting drawings. The expert's cognitive activity is based on a tree structure including a small group of concurrent actions in each branch (up to five in the primary and up to six in the secondary levels of cognitive processing). However, in the novice's protocol, cognitive performance has been divided into many groups of concurrent actions with a tree structure including many concurrent actions in each branch, with up to 13 in the primary and up to 16 in the secondary levels. The novice deals with three times as many concurrent actions as the expert, whereas the expert seems to have control of his cognitive activity and governs his performance in a more efficient way than the novice, because his cognitive actions are well organized and clearly structured. Thus, the structural organization in the expert's concurrent cognitive actions may be the reason for the expert's relatively high performance compared with the novice's.

While the expert's highly focused attention might play a major role in his higher performance and productivity, the novice's widely distributed and defocused attention might play a major role in the higher rates of certain types of discovery, by making remote associations available. This raises a question: may this unstructuredness in cognitive activity accidentally lead to certain type of discoveries? In this case, can we talk about the positive affect of unstructuredness on discoveries, while it may also be the cause for the drop in the performance? The structuredness in cognitive activity may govern the performance in design process, while the unstructuredness may support the occurrence of a certain type of discoveries, making remote associations accessible. Thus, this may explain the novice's success in creating novelty and the expert's success in performance called expertise.

Acknowledgements

This research was funded by the Australian Research Council, through a grant to John Gero. Our special thanks to Masaki Suwa for the information about the coding scheme and video tapes of the design protocols and to Simeon Simoff for his support in the statistical analysis of the early phases of this study.

Note

1 This research study was conducted while the first author was a Visiting Scholar at the Key Centre of Design Computing and Cognition.