STRATEGIC KNOWLEDGE DIFFERENCES BETWEEN AN EXPERT AND A NOVICE DESIGNER

MANOLYA KAVAKLI
Charles Sturt University, Australia
and
JOHN S GERO
University of Sydney, Australia

Abstract. This chapter investigates the differences in performance between an expert and a novice in terms of their respective strategic knowledge. We examined conceptual design protocols of an expert and a novice, and found that the expert's cognitive activity and productivity in the design process were almost three times as high as the novice's. The possible reason for this is the difference in their strategic knowledge. The expert's cognitive processing is structured such that it stays within the limits of human short term memory. This provides empirical evidence for a different strategic knowledge that may be developed with experience. The expert's strategic knowledge allows him to use a smaller number of processes and to form different groupings of processes.

1. Introduction

In this chapter, we explore the effect of strategic knowledge in conceptual design process by discussing the differences in cognitive processes and groupings between a novice and an expert. In our previous studies, 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 (Kavakli et al., 1999). We investigated the structure of cognitive actions in the design protocols, and found that there is evidence for the coexistence of the cognitive actions (Kavakli and Gero, 2001). Certain groups of cognitive actions increase and decrease in parallel with each other in the protocols of the novice and expert designers. We suggested that the differences in the performance of designers could be attributed to the differences in the structure of those concurrent cognitive actions. Investigating the concurrent cognitive actions, we found that the expert's cognitive actions are well organized and clearly structured, while the novice's cognitive performance has been divided into many groups of concurrent actions. (Kavakli and Gero, 2002). In this chapter, we focus on explaining the difference in performance between the expert and novice in terms of their respective strategic knowledge. Our hypothesis is that structuring their respective actions is what constitutes their strategic knowledge and that this knowledge is different for each, and is the cause of their behavioural differences.

2. Strategic Knowledge, Chunks, and Cognitive Segments

Beginning in the early 1950s a number of researchers (Hovland, 1952, Miller, 1953, Attneave, 1954) noted that if an individual's response tendencies change with experience then observing his behaviour yields information as to what experiences he has had. This approach suggests the value of analyzing the detailed sequence of both observable and the inferred operations performed by an individual engaged in a cognitive task, that is, engaged in the process of taking in, storing, transforming, and retrieving information (Estes, 1976). This kind of information processing theory necessitates close attention to the information processing requirements of a task and thus is often useful in uncovering constraints on the learner that would not otherwise be apparent. We take sketching in conceptual design as a form of mental imagery processing (Kavakli and Gero, 2001). Mental imagery processing (Kosslyn et al.,

1984) 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 due to the limit of human short term memory.

Broadbent (1971) maintained that information is recorded in only two forms: transient excitations and long-term records. He compared short-term memory to address registers in a computer. The registers themselves do not store data; instead they point to data held in another storage medium. Short term memory consists of a limited number of *working registers*, each of which excites or activates some record in a long-term storage. If short-term memory is maintained by working registers, a basic question is how many registers are available. Using a variety of evidence, Miller (1956) showed that short-term memory can hold about seven *chunks* of information, where a chunk is the amount of information in a schema – a single bit, a decimal digit, a word, or a phrase. The basic property of a chunk is not its size, but its unity as a well-learned, familiar pattern (Sowa, 1984). Broadbent (1975) argued that a better estimate is three working registers rather than seven, because only three or four items can be recalled with a high degree of accuracy, although the average span of short-term memory is about seven items. Extra items beyond three or four are remembered accurately only if they have associations to other items in the list. When people recall items from a familiar category, they tend to group their responses in bursts of two or three.

The design protocols used herewere collected as a retrospective report after the design session. We used the content-oriented protocol analysis method to investigate concurrent cognitive actions of designers. These protocols were divided into segments, indexed and coded according to the information categories classified by Suwa and Tversky (1997). Information on procedures of protocol parsing and coding can be found in Kavakli & Gero (2001 and 2002). A *cognitive segment* consists of cognitive actions that appear to occur simultaneously. We assume these cognitive actions as chunks in Miller's definition. We found that the design protocol of the expert includes 2,916 actions (chunks) and 348 segments, while the novice's protocol includes 1,027 actions and 122 segments. In both protocols, each segment includes 8 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.

3. Concurrent Cognitive Processing

The cognitive activity of designers appears to be parallel to the drawing production on pages in both design protocols. Cognitive 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. 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. Therefore, we could look for the reason for the drop in the performance in concurrent cognitive actions, rather than only within a certain group of cognitive actions (Kavakli & Gero, 2002). We investigated the concurrent cognitive actions in three levels of a tree-like structure: root, primary branching, secondary branching.

3.1. Concurrent Cognitive Processing

First, we investigated the major groups of cognitive actions (in terms of pages produced by the designers) that indicate strong correlations in both design protocols. As can be seen in Table 1 there are strong correlations between major categories of cognitive actions in the root in both design protocols. There are differences here between the expert and novice that will impact on our later analysis.

TABLE 1. Correlation coefficients of cognitive actions in pages

expert-page	*Drawing*	*Looking*	*Perceptual*	*Functional*	*Goals*	*Moves*
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*	*Looking*	*Perceptual*	*Functional*	*Goals*	*Moves*
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

3.2. Primary Branching of Concurrent Cognitive Processing

Second, we investigate the correlations between subcategories of cognitive actions to find the structure in concurrent cognitive processing. Our purpose here is to explore the top-down correlations between a specific group of drawing actions (Dc: Depicting drawings) and others. We will narrow down our exploration and focus on only the concurrent actions highly correlated with depicting drawings, Table 2. Table 2 gives the full list of the correlation values of cognitive actions, while Table 3 only lists the codes and definitions of highly correlated concurrent actions with Depicting Drawings in both design protocols. The full list of the codes can be found in Tables A1 to A4 in the Appendix. A full list of definitions can be found in Kavakli & Gero (2001 and 2002).

TABLE 2. Correlations with Depicting Drawings

Action code	**novice**	**expert**	**Action code**	**novice**	**expert**
Drf	0.34	0.03	Frei	0.21	0.20
Dts	0.98	0.58	Fo	0.51	0.83
Dtd	-0.75	0.25	Fnp	0.60	0.31
Dsy	0.74	0.35	Fop	0.21	0.68
Dwo	0.75	0.32	Fi	0.26	0.24
L	0.99	0.81	G1-1	-0.29	0.45
Psg	0.71	-0.17	G1-2	0.73	0.67
Posg	0.64	0.27	G1-3	0.21	0.44
Pfn	0.66	0.45	G1-4	0.85	0.14
Pfp	0.90	0.15	G2	0.38	0.34
Pof	-0.27	0.53	G3	0.71	0.21
Prp	0.98	0.74	G4	0.58	0.19
Prn	0.28	0.70	Ma	-0.29	0.31
Por	0.92	0.57	Mod	0.60	0.07
Fn	0.86	0.75	Moa	0.89	0.69

We categorize the concurrent cognitive processing into two groups: primary branching and secondary branching. Primary branching lists the cognitive actions that directly correlate with depicting drawings. Secondary branching lists the cognitive actions that highly correlate with each action in primary branching. Table 4 lists the primary concurrent actions highly correlated with depicting drawings. In this and the following tables, “-” refers to negative strong correlations, "~" refers to substantial correlations and blank line refers to the cognitive actions which do not correlate. Otherwise, action code refers to positive strong correlations.

TABLE 3. Concurrent Action Codes

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

TABLE 4. Primary Concurrent Actions Correlated with Depicting Drawings (Dc)

Root Action Code	**Primary Action Code: Novice**	**Primary Action Code: Expert**
Dc	L	L
	Dts	~Dts
	Por	~Por
	Prp	Prp
		Prn
	~Fo	Fo
	Fn	Fn
	Moa	~Moa
	G1-2	~G1-2
	Dwo	
	Dsy	
	-Dtd	
	Psg	
	Pfp	
	G1-4	
	G3	

( ) positive strong correlation
(-) negative strong correlation
(~) substantial correlation

As we can see in Table 4, 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, in the expert's design protocol, there are also strong correlations between depicting drawings (Dc) and:

- creation of a new relation (Prn)
- revisited thought of a function (Fo).

There are weak correlations in these categories in the novice's. 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 indicates a long list of correlations:

- 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).

Besides these, tracing over the sketch on a different sheet (Dtd) is also strongly negatively correlated with depicting drawings (Dc) for the novice. On the contrary, discovery of a new space as a ground (Psg) is, surprisingly, negatively (though weakly) correlated for the expert.

3.3. Secondary Branching

Table 5 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 that strongly correlate with the primary concurrent action in the first column.

TABLE 5. Secondary Concurrent Actions Correlated with Depicting Drawings (Dc)

Primary Action Code	**Secondary Action Codes: Novice**	**Secondary Action Codes: Expert**
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		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	Dc, Dts, L, Posg, Prp, Prn, Por, G1-2, G1-4, G2, G3	
Dsy	Dc, Psg, Pfp, -Pof, Fn, Fnp, Mod, Moa	
Dtd	-Dc, -Dts, -L, -Pfn, -Prp, -Por, -Fo, -Fi, -G1-4, -G3	
Psg	Dc, Dts, Dsy, L, Pfp, Prp, Fn, Fnp, -G1.1, G1-2, G4,-Ma, Mod, Moa	
Pfp	Dc, Dts, Dsy, L, Psg, Fo, Fi, G3	
G1-4	Dc, Dts, -Dtd, Dwo, L, Posg, Prp, Por, Fo, G1-2, G2, G3	
G3	Dc, Dts, -Dtd, Dwo, L, Posg, Pfn, Prp, Por, Frei, Fo, Fop, G1-3, G1-4, G2	

( ) positive strong correlation
(-) negative strong correlation
(~) substantial correlation

We can see in Table 5 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 5 indicates that the expert's cognitive activity is based on the coexistence of a limited number of actions (5 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 (Miller, 1956). Whereas the expert's working registers stay in the limits. In the context of chunks defined by Sowa (1984), as we remarked in the beginning of this chapter, the main property of a working register is its unity as a well-learned, familiar pattern. Do the structure of working registers, as shown in this case study, have some reference to well-learned design strategies through experience?

4. Tree Structure of Concurrent Cognitive Processing

Taking it one step further, now we will group the secondary concurrent actions to see the associated groups of working registers suggested by Broadbent (1975) who argued that a better estimate is three working registers rather than seven, because only three or four items can be recalled with a high degree of accuracy, although the average span of short-term memory is about seven items. Our purpose in this chapter is neither to test nor verify the number of working registers in design cognition, but to use it as a basis for structural differences in concurrent cognitive processing. Table 6 is the classification of the secondary concurrent actions into associated groups.

TABLE 6. Tree Structures of Concurrent Actions Correlated with Depicting Drawings (Dc)

NOVICE		**EXPERT**	
Primary Action	**Secondary Action**	**Primary Action**	**Secondary Action**
L	**A-1** {Fo}, **B**, **C**, **D**	L	**A**
Dts	**G**, **-J-1**{G4}, Dc	~Dts	Dtd
Por	**A**, **B**, **D-2**{Psg, Pfp}, **E**	~Por	**A-1**{Dc}
Prp	**A-1** {Fo}, **B**, **C**, **D**	Prp	**A**, Pof
		Prn	Dc
~Fo	**B-1**{Dwo}, **H**, Por	Fo	**A**
Fn	**A-2**{Por, Fo}, **D-2**{Dts, Posg}, **F**	Fn	Dc
Moa	**A-2**{Por, Fo}, **D-1**{Posg}, **F-1**{-Pof}, **K**	~Moa	Dc, Fop, **C**
G1-2	**A-1** {Fo}, **D-1**{Pfp}, **J**, Dwo, G1.4	~G1-2	**C-1**{Fn}
Dwo	**A-1** {Fo}, **B-1**{-Dtd}, **D-2**{Psg, Pfp}, **E**, Prn		
Dsy	**D-2**{Dts, Posg}, Dc, **F**, **K**, Moa		
-Dtd	**-A**, -Dts, **-G**, -G1-4, -G3		

Psg	**A-2**{Por, Fo}, **C**, **D-1**{Posg}, **J-1**{Prn}, **K**, Dsy		
Pfp	**A-2**{Por, Prp}, **D-1**{Posg}, Dsy, Fi, G3		
G1-4	**A**, **B**, **D-2**{Psg, Pfp}, **E**		
G3	**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	- strong negative correlation ~ substantial correlation

In the expert's design protocol in Table 6, as implied by the fourth column, looking actions (L) highly correlate 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 concurrent actions appears more than once in both the expert's ad novice's design protocols, we call this list of actions (including the action code in the first column) a group and label it Group A in Table 6. Group C is another example of this type of grouping. It consists of a group 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 parenthesis {}, for example, A-1{Fo} means group A less one member, Fo.

As we can see in Table 6, 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. For each action code, the associated groups of concurrent actions range from 1 to 3 in the expert's cognitive processing, while they range from 3 to 5 in the novice's.

5. Conclusion

This case study shows the effect of strategic knowledge on performance. We may categorize the differences between a novice and an expert in terms of:

- productivity
- rate of cognitive activity
- structure of concurrent actions
- number of cognitive processes and groupings
- strategic knowledge.

The expert in our experiment governs his performance in a more efficient way than the novice, because of the clear organization and the structure of his cognitive actions. We have provided evidence that the expert's cognitive activity is based on a tree structure including a small group of concurrent actions in each branch (up to 5 in the primary and up to 6 in the secondary branching 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 14 in the primary and up to 16 in the secondary levels. The novice deals with 2.8 times as many concurrent actions as the expert (14 compared to 5 associated groups). 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. Is this coincidental or an indicative of the value of his strategic knowledge to govern his performance?

We have used Miller's magical number seven (Miller, 1956) to support our hypothesis. We have applied the 7 +/- 2 test to both protocols and found that the groupings for the novice fail the test whilst those of the expert pass it. Thus, the number of concurrent cognitive actions of the expert is between the limits of human short term memory, whereas, it is beyond the capacity of human short term memory for the novice. We have also used Broadbent's associated grouping test (Broadbent, 1975) based on maximum 3 to 4 members. We have found that for each action code, the associated groups of concurrent actions range from 1 to 3 in the expert's cognitive processing, while they range from 3 to 5 in the novice's. The number of associated groups for the novice fail the Broadbent's test, whilst those of the expert pass it. These tests provide empirical evidence for a different strategic knowledge that structure their respective cognitive actions, and that may be the cause of the difference in performance between the novice and the expert.

These tests also provide evidence for a systematic expansion in primary and secondary branching in the expert's design protocol, and an exhaustive search in the novice's. Adelson and Soloway (1985) also report evidence on a systematic expansion in the experts' design protocols in their experimental findings. Granovskaya et al. (1987) stated that 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. Our experimental results highlight the nature of this insight and suggest that strategic knowledge governs both cognitive activity and professional performance. Even with this limited evidence, our case study raises a question: to become experts, do designers have to learn strategies that would serve as an aid for perceptual and cognitive grouping?

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Appendix

Tables A1 to A4 list the codes used in the protocol study reported.

TABLE A1. 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

TABLE A2. 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

TABLE A3. Codes of F-actions

F-actions:Functional actions related to new functions	*F-actions:Functional actions related to revisited*	*F-actions:Functional actions related to*

	functions	*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 A4. 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

This is based on a paper presented at *SKCF01*.

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