Dissociation of Design Knowledge

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Abstract

It is often noted that successful designing requires two types of knowledge: explicit, articulate, domain-specific knowledge, and inarticulate, domain-independent, procedural knowledge. Neuropsychological evidence is provided for a dissociation between the two types of knowledge. This reinforces the reality of the distinction. It is further suggested that the inarticulate, procedural knowledge is not knowledge in the traditional sense of the word, but consists of *mechanisms* to support "ill-structured" representations and computations. This implies that learning environments – like the design studio – that provide students with *practice* in groping and coping with ill-structured, real-world design problems must be an integral part of design education.

Let him be educated, skillful with pencil, instructed in geometry, know much history, have followed the philosophers with attention, understand music, have some knowledge of medicine, know the opinions of the jurists, and be acquainted with astronomy and the theory of the heavens.
-- Vitruvius (on the education of the architect) quoted in Broadbent (1973, p. 4)

1. Introduction

The organizers of this conference differentiate between two types of design knowledge:

> One kind of knowledge [Type 1] is domain-related and technical; how does a building stand up? What are the basic components of a compiler or graphics system? What are the procedures in a hospital? How are computer chips fabricated? Another kind of knowledge [Type 2] seems less domain-specific and seems largely procedural. It deals *with managing the processes of designing: how to structure and define a problem, how to identify new issues for an already defined problem? how to generate non-obvious alternatives?* The second kind of knowledge cannot be easily measured, and the effectiveness of the knowledge *interacts with other dimensions of a person, such as personality, social skills and self-discipline*. [italics added]

I am not sure that the declarative / procedural categories are rich enough to capture the distinction, but I am sure that there is a crucial distinction to be captured. Type 1 knowledge is easily identified, organized, articulated and disseminated in textbooks and classroom lectures. Type 2 knowledge is more illusive. It is passed down in more subtle, inarticulate ways.

The main goal of this chapter is to argue that the distinction between Type 1 and Type 2 knowledge has a neuropsychological basis, as demonstrated by anatomical dissociation, and to show the consequences on the design process of a deficit in Type 2 knowledge. We begin by discussing the importance of finding a neuropsychological dissociation corresponding to an intuitive or psychological distinction; review some famous cases of patients that seem to exhibit a dissociation between Type 1 and Type 2 knowledge; review the performance of an architect with a lesion to the right prefrontal cortex, that seems to leave Type 1 knowledge intact but grossly impairs Type 2 knowledge, rendering him incapable of designing; explain the deficit in terms of theoretical ideas developed in Goel (1995); and conclude by drawing some lessons for design education.

2. Importance of Neuropsychological Dissociations

The proposed distinction between Type 1 and Type 2 design knowledge is an intuitive, functional distinction, perhaps based on some psychological theory. But we know that our intuitions are often wrong and that psychological theories are notoriously underconstrained. More generally, functional individuations are not causally constrained. We usually use such individuations just when we do not know the underlying causal structure. This devalues the currency of functional distinctions. But if we can show that our functional distinctions map onto causally individuated neurophysiological structures, then we can have much greater confidence in the functional individuation.

By way of an example, suppose that we individuate the following three functions on the basis of behavioral data: (f1) raise left arm, (f2) raise left foot, (f3) wiggle right ear. If these functions can be mapped onto three causally differentiated structures in a one-to-one fashion, we would be justified in claiming to have discovered three distinct functions. If, however, all three of our behaviorally individuated functions map onto one causally differentiated structure, in a many-to-one fashion, we would say that our functional individuation was too fine grained and collapse the distinctions until we achieved a one-to-one mapping. That is, raising the left arm does not constitute a distinct function, but the conjunction of the three do constitute a single function. If we encountered the reverse situation, where one behavioral function mapped onto several causally distinct structures, we would conclude that our individuation was too coarse-grained and refine it until we achieved a one-to-one mapping. One final possibility is a many-to-many mapping between our functional individuation and casually individuated structures. Here we would have a total cross-classification and would have to assume that our functional individuations are simply wrong and start over again.

One way of discovering these mappings is through studies of patients with brain lesions. Brain lesions result in selective impairment of behavior (cognitive and otherwise). Such selective impairments are called dissociations. A single dissociation occurs when we find a case of a lesion in region *x* resulting in a deficit of function *a* but not function *b*. If we find another case, in which a lesion in region *y* results in a deficit in function *b* but not in function *a*., then we have a double dissociation.

The most famous example of a double dissociation comes from the domain of language. In the 1860's Paul Broca described patients with lesions to the left posterior inferior frontal lobe who had difficulties in the production of speech but were quite capable of speech comprehension. This is a case of a single dissociation. In the 1870's Carl Wernicke described two patients (with lesions to the posterior regions of the superior temporal gyrus) who had difficulty in speech comprehension, but were quite fluent in speech production. The addition of this observation results in a double dissociation.

With respect to design knowledge, if we are presented with a patient in whom a lesion in area *x* impairs the ability to access Type 2 design knowledge, but allows unimpaired access to Type 1 design knowledge, then we have a case of single dissociation. If other cases are found where a lesion in area y impairs the ability of the patient to access Type 1 knowledge, but allows unimpaired access to Type 2 design knowledge, then we have evidence for a double dissociation. In either case we have evidence for differences in causal mechanisms underlying Type 1 and Type 2 knowledge. In the case of a double dissociation we would have evidence for two distinct neurophysiological mechanisms.

3. Relevant Cases

The most relevant cases for us come from the frontal lobe patient literature. There are many reports of patients, who are by in large neuropsychologically intact, but cannot successfully function in the world. The literature originates with Harlow's (1868) classic description of Phinas Gage. Gage was a railroad foreman who had a four foot iron tamping rod pass through his skull in a freak accident. Gage survived, and in many respects continued with his life. However, Harlow noted that prior to the injury Gage was mild mannered and "considered a shrewd businessman, energetic & persistent in executing all his plans." But after the injury he would devise "many plans of future operation but discarding them before they were executed." He was also fitful, irreverent, obstinate, and impatient of restraint or advice. There seemed to be an imbalance between his "intellectual faculty" and "animal propensities". His friends said of him that he was "no longer Gage."

Another famous description is Penfield's (Penfield & Evans, 1935) report on the difficulties in planning dinner experienced by his sister fifteen months after the removal of her right frontal lobe:

> When the appointed hour arrived she was in the kitchen, the food was all there, one or two things were on the stove, but the salad was not ready, the meat had not been started and she was distressed and confused by her long continued effort alone. It seemed evident that she would never be able to get everything ready at once... Although physical examination was negative and there was no change in personality or capacity for insight, nevertheless the loss of the right frontal lobe had resulted in an important defect. The defect produced was a lack of capacity for planned administration.... (p. 131)

In the more recent literature, Eslinger & Damasio (1985) describe the patient EVR, a successful 35 year old accountant who underwent an operation for the removal of a large orbitofrontal meningioma (a type of tumor originating in the meninges, the protective membrane surrounding the brain). After the operation EVR tested in the above average range to superior range on IQ and memory tests, yet was unable to hold a job and function successfully in the world (pp.1731-1732):

> After a 3-month recovery period, he returned to accounting and bookkeeping.... He soon became involved in a home-building partnership with a former coworker, a man of questionable reputation who had been fired from the company... The business failed and he had to declare bankruptcy..... Thereafter, he drifted through several jobs. He worked as a warehouse laborer, as a building manager, and as an accountant ... but was fired from each. Employers complained about tardiness and disorganization, although basic skills, manners, and temper were appropriate. Similar difficulties led to a deterioration of his marital life.... Unable to hold a job and separated from his family, EVR moved in with his parents....Employment problems continued.... He needed 2 hours to get ready for work in the morning, and some days were consumed entirely by shaving and hair-washing. Deciding where to dine might take hours... He would drive to each restaurant to see how busy it was.... Purchasing small items required in-depth consideration of brands, prices, and the best method of payment. He clung to outdated and useless possessions, refusing to part with dead houseplants, old phone books, six broken fans....

All of these observations speak of difficulties in judgment, decision-making, and problem solving in real-world, open-ended situations. Often the problem solving involves planning and look-ahead components. Perhaps the most relevant case for our purposes is that of patient PF, an accomplished architect, reported by Goel and Grafman (2000). It provides an illustration of what happens to the design process when Type 2 design knowledge is unavailable.

4. Patient PF: Impairment of Type 1 Knowledge[1]

Goel and Grafman (2000) report the case of patient PF, a right handed 57 year old Caucasian male architect, who suffered from a predominantly right hemisphere lesion to the prefrontal cortex (though some minor anterior left frontal damage was also present).

PF earned a graduate degree in Architecture from Yale University. He scored in the 98th percentile on the Graduate Record Examination in math and science. After graduation he practiced in the USA until the mid-1970s and then moved to Spain to work on a long term "dream project". He was successfully self-employed in Spain until his illness. At the time of testing, PF had IQ and memory scores in the superior to excellent range, his ability to draw was intact, yet he was unable to design. He was involuntarily retired and lived at home with his mother.

To explore the nature of his deficit, Goel and Grafman matched him for age and education with a 54 year old Architect and engaged both in a simple architectural design/planning task. Both subjects were asked to propose a redesign for our lab space. They were given the following problem statement specifying a set of constraints and encouraged to ask for additional information as necessary:

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[1] Much of this section (including Figures 1 – 4) is reproduced from Goel and Grafman (2000).

> Our lab space is located in Room 5D51. It currently houses three scientists and five research assistants. Another scientist is expected in January. The number of research assistants can increase up to 16 during the summer months.
> The space is used for reading, writing, computing, telephone conversations, and so on. In fact, we do all of our work in this space except for seeing patients. Some of us spend up to 10 hours per day there. It is a very dismal environment.
> Your task is to reorganize, redesign, reconfirm the space such as to increase our comfort and productivity. We do not have a budget for the redesign. However, we do have the option of exchanging some of our furniture at the surplus store, and perhaps we can pool personal time and resources to do some painting and cleaning.
> You have two hours to propose a design. You may spend up to 15 minutes of the first hour in the lab space. While there, you may measure, make notes and sketches, and ask anyone there any questions you think relevant. You may revisit the lab for 10 minutes anytime during the second hour. Please begin.

Both subjects reported having experience designing office spaces and noted that this was a very easy problem for them.

The first thing to note about PF's performance is that his explicit (Type 1) knowledge of design is intact. An episode level analysis of the data provides a measure of goals/subgoals and strategies pursued by subjects. It is a content analysis. It gives an indication of the knowledge the subjects bring to the problem space and the issues they consider. Table 1 shows the problem solving episodes engaged in by our patient and control subject. As can be seen in Table 1, both subjects considered issues ranging from information about users (e.g. numbers, categories), their goals (e.g. a quieter environment), behaviors/activities the users need to engage in (e.g. meetings, writing), the functions the artifact/space needs to support (e.g. circulation patterns), and the actual structure of the artifact (e.g. printers, workstations, dimensions). Both the control and patient displayed the sophisticated knowledge base one would expect from experienced architects.

However, there are significant differences in the problem solving behavior of the patient and control. Figures 1 & 2 show the temporal distribution of design-level statements for the control and patient, aggregated over five-minute intervals. The control's temporal distribution of statements is quite typical of designers (Goel, 1995). He begins by problem structuring and has it largely completed in the first quarter of the problem solving session. The next part of the session is devoted to preliminary design, followed by design refinement and then detailing, each in roughly equal proportion. The whole process is accompanied by some self-monitoring and the phases reoccur as needed throughout the session.

The patient's progress through the problem space is quite different from that of the control subject (Figure 2). The patient spends most (two-thirds) of the session in problem structuring mode. The preliminary design phase, occurs at the tail end of the session. Its duration is short; it is accompanied by much self monitoring and a great many miscellaneous statements; and as we will see shortly, the patient's movement through this phase is erratic and lacks progression. It is a phase that the patient has enormous difficulty with. At the 87 minute mark, the beginning of the refinement period, the patient notes "lets start again." Refinement of this proposal occurs during the last few minutes and the session ends abruptly.

Table One: Itemization of modules and submodules utilized by patient (PF) and control (NC). The 'x' indicate utilization.

PF	NC		PF	NC	
x	x	Users	x	x	Communal Facilities & Space
x	x	numbers	x	x	furniture
x	x	class/ categories	x	x	filing cabinets
x	x	relationship between users	x	x	misc equipment
x	x	changes over course of year	x	x	printer
x	x	work habits		x	message board
x		source of discomfort		x	photocopying
x	x	Activities in space	x	x	closet space
x	x	experiment design & analysis	x	x	storage space
x	x	reading & writing	x	x	entrance zone
x	x	meetings	x	x	dimensions
x	x	Social Concerns	x	x	configuration
x	x	social clustering/ social hierarchy	x	x	refrigerator
x	x	community space	x	x	microwave
x	x	private space		x	Lighting
x	x	character of space		x	natural light
	x	personalization of space		x	task lights/ personal lamps
x	x	noise levels		x	florescent lights
x	x	Circulation Patterns	x	x	Border Conditions
	x	cul de sac/	x	x	walls
	x	dead space		x	ceilings
	x	congestion		x	windows
x	x	Private Facilities & Space	x	x	door
x	x	workstations		x	flooring
x	x	computers		x	venting
	x	seating		x	orientation (N, S, E, W)
x	x	dimensions	x	x	dimensions
x	x	configuration	x		Cleaning/maintenance

Overlaid on top of the temporal distribution of design-level statements in Figures 1 & 2 are the key drawings made the by the subjects and some highlights of the session. Drawings depict the generation and development of ideas/concepts. As such they constitute states in the designers' problem space. Figures 3 & 4 show the actual drawings made by the subjects and the type of transformations that lead from one drawing/idea to the other.

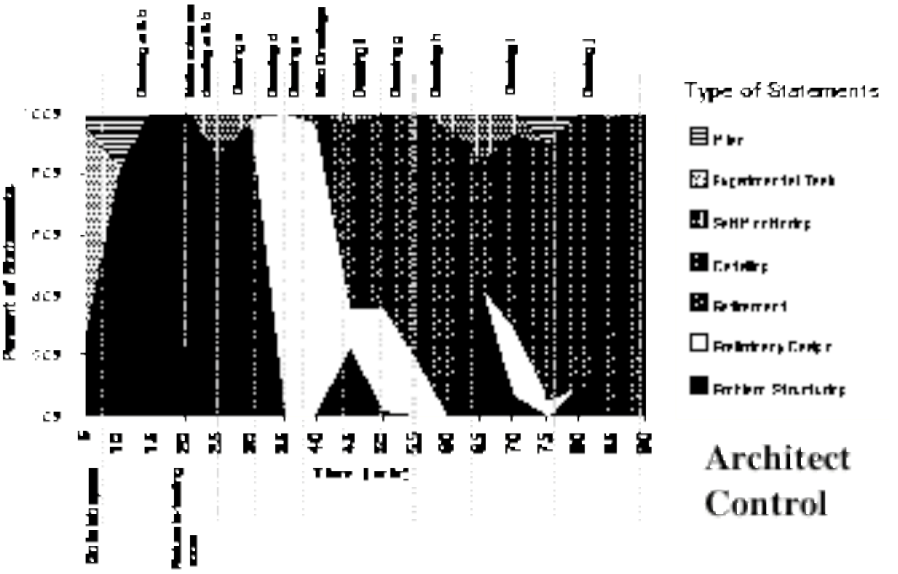

Figure One: Control's design-development statements aggregated into 5 minute intervals. Drawings and key events are overlaid on top.

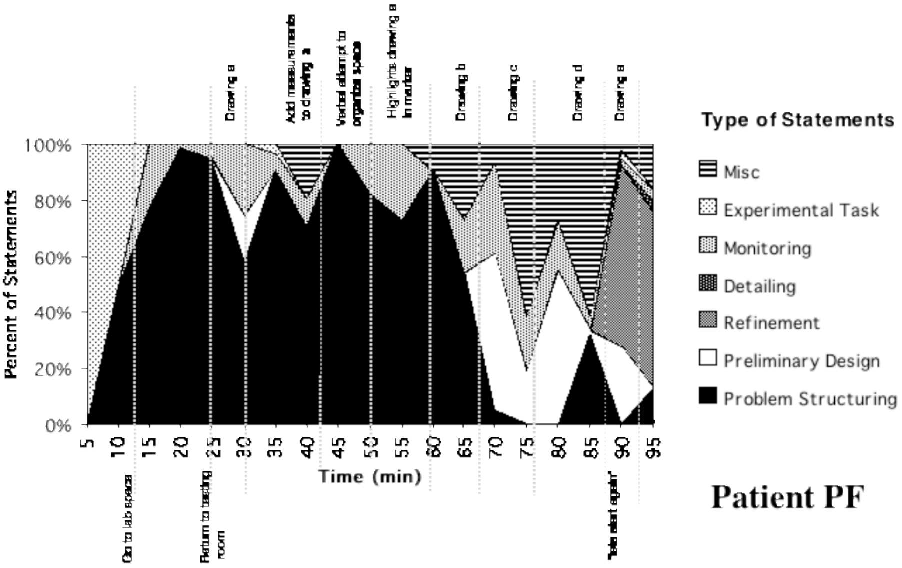

Figure Two: Patient's design-development statements aggregated into 5 minute intervals. Drawings and key events are overlaid on top.

There are nine states in the control's problem space (Figure 3), a start state (a & b), a goal state (j) and seven intermediate states (c - i). The starting state for the control is drawing (a) of the existing lab space and the accompanying measurement drawing (b). Both drawings were made in the lab space. Three of the intermediate states belong to the preliminary design phase (c - e); four belong to the refinement phase (f - i); and the final state belongs to detailing (j). The preliminary design states are all quite abstract. He begins by considering "circulation patterns" in drawing (c). This pattern constitutes his kernel idea. It is developed and transformed to deal with the issue of and "social organization" (d) and "permanent and transient spaces" (e). The refinement drawings are structural. They depict workstations, tables, doors, windows, and corridors. The subject transforms state (e) into a proposal (drawing f) (half way during the session) that he considers "reasonable". However he thinks the center condition can be improved. He therefore holds the perimeter conditions constant and transforms the center in drawing h. He rejects drawing (h), returns to drawing (f) and transforms it into drawing (g). He is happy with the idea depicted by drawing (g). He now shifts gear and begins to detail and fine tune the proposal, first in section (drawing i) and then in plan (drawing j).

The movement from states (c) to (g) is underwritten by lateral transformations. A *lateral transformation* is one where movement is from one idea to a slightly different idea rather than a more detailed version of the same idea (Goel, 1995). The transformation of state (g) to (i) and from (i) to (j) is underwritten by vertical transformations. A *vertical transformation* is one where movement is from one idea to a more detailed version of the same idea (Goel, 1995).

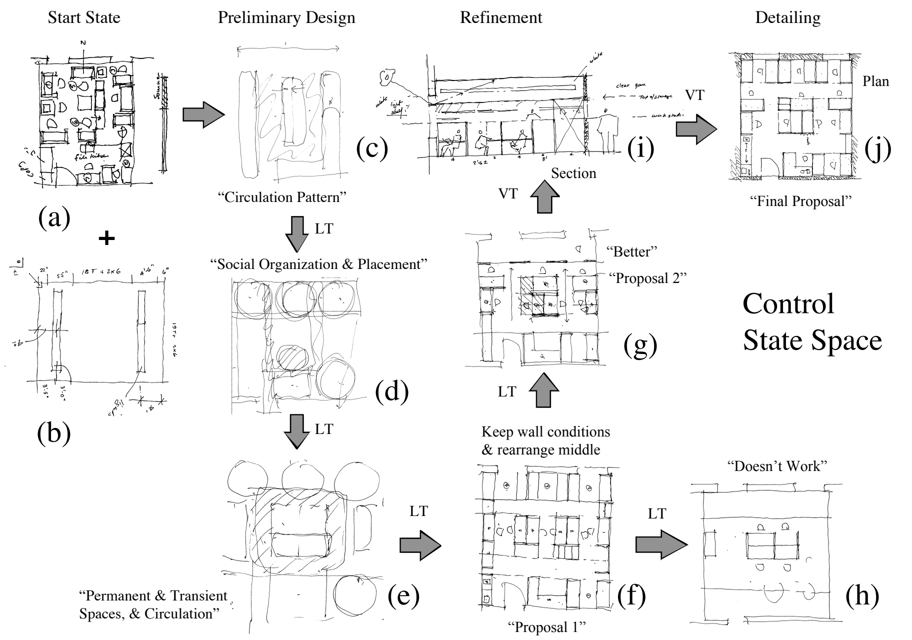

Figure Three: Control's state space and transformation functions. LT = lateral transformation; VT = vertical transformation.

An analysis of the patient's state space tells a very different story. There are five states in the patient's problem space (Figure 4), a start state (a), a goal state (e) and three intermediate states (b - d). The start state drawing of the existing lab space (a) was completed by the patient from memory in the testing room. It is as detailed and accurate as the control's drawing. The patients final state drawing (e) was completed during the refinement phase. The three intermediate drawings (b - d) were completed during the preliminary design phase. The first of these drawings (c) –

the kernel idea – occurs two-thirds way into the session. Unlike the preliminary drawings of the control, the patient is concerned with arranging furniture right from the start. But perhaps the most dramatic difference between the patient and control is that the patient's three preliminary design drawings are fragmentary and unrelated.

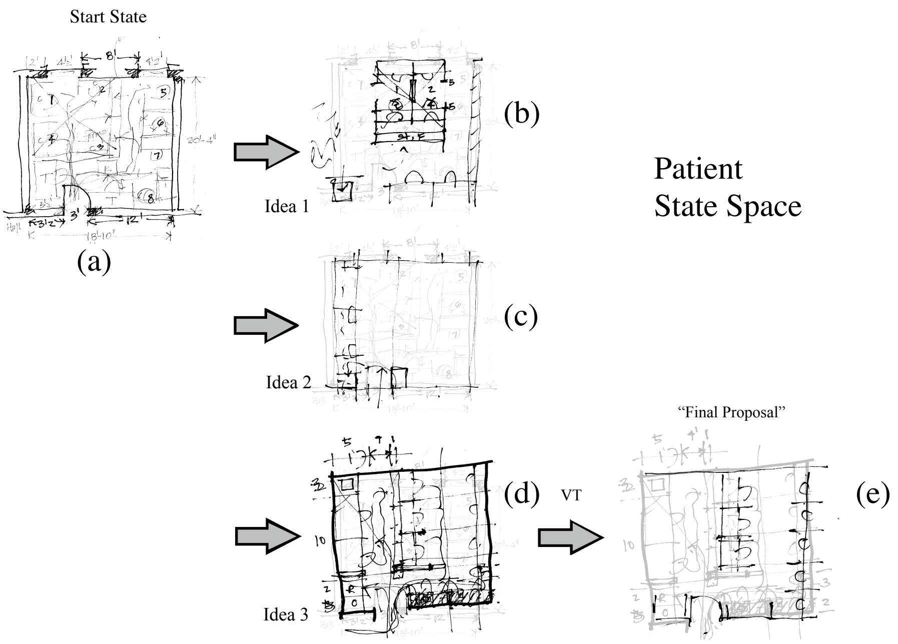

Figure Four: Patient's state space and transformation functions. LT = lateral transformation; VT = vertical transformation. Drawings (b) to (e) were executed on transparent tracing paper on top of drawing (a).

Preliminary design sketches are, almost by definition, fragments of ideas. Designers do not generate several independent fragments and choose between them. They generate a single idea/fragment and develop it through transformations (lateral or vertical) to a point it is complete and can be evaluated (Goel, 1995). The patient has made several (successful) attempts to generate idea fragments. But he is unable to develop and explore these ideas through the application of lateral transformations. Each of his preliminary drawings must be treated as independent idea/fragments. Indeed, he tries to articulate the difficulty he is experiencing as follows:

> You see, normally, what I would have, even as a student, I'd be -- there would be sketches on top of sketches. And I could -- it would be progressive. Here I seem to be doing several different thoughts on the same piece of paper in the same place, and it's confusing me. So, instead of the one direction that I had at the beginning, I have three or four contradictory directions with not a kind of anchor to work from....

On generating drawing (d) 87 minutes into the session, he says "lets start again". The only idea/drawing transformation he engages in is from (d) to (e). This is a vertical transformation where he fine-tunes the proposal.

Further evidence of the patient's difficulties with the preliminary design phase is provided by analyzing the "aspects of design development" considered by the control and patient during the four phases of design development. Figure 5 shows the percentage of design development statements (problem structuring, preliminary design, refinement, and detailing) the control subject devotes to the consideration of people (users), their goals/purposes, the behaviors that need to be supported, the function the artifact needs to serve, and the structure of the artifact itself. One can see that during problem structuring and preliminary design the majority of the statements are devoted to abstract, nonstructural aspects of the design having to do with users, goals, behaviors, and functions. This distribution shifts with the refinement phase, where function and structure dominate, and again in the detailing phase, where structure dominates. For example, during the structuring phase the control considers issues of social hierarchy (research assistants vs. scientists). This is propagated and translated into structural arrangement in terms of giving the scientists more spacious workstations and placing them in corner locations.

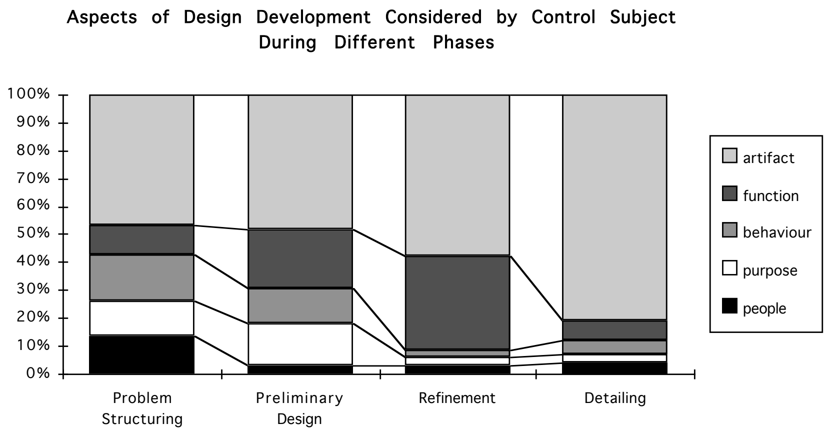

Figure Five: Aspects of design development considered by control subject during different phases of problem solving

Figure 6 shows the corresponding data for patient PF. It contains only three phases (because the patient did not enter into a detailing phase). The level of abstractness of the statements in the patient's problem structuring phase is quite similar to the control's. He solicits and generates much relevant information about people, purpose, and behaviors. The patient's refinement phase distribution is also not unlike the control's. However, the patient's preliminary design phase is dramatically different. Whereas the control carries through the information regarding people, purpose and behavior through to the preliminary design phase (and in fact through to refinement and detailing) and uses it to guide the emerging design, *the patient is unable to carry through this information and use it to guide problem solving.*

PF provides an intriguing example of a trained architect whose explicit knowledge of design is intact (as evidenced by the episode-level analysis in Table 1) but he is unable to participate in even very simple design problem solving activities. I think that the breakdown we are observing is quite consistent with the Type 1 and Type 2 distinction in design knowledge that we began with. His Type 1 knowledge is intact but he is unable to access Type 2 knowledge. I would now like to review four neuropsychological theories that attempt to explain the observed deficit.

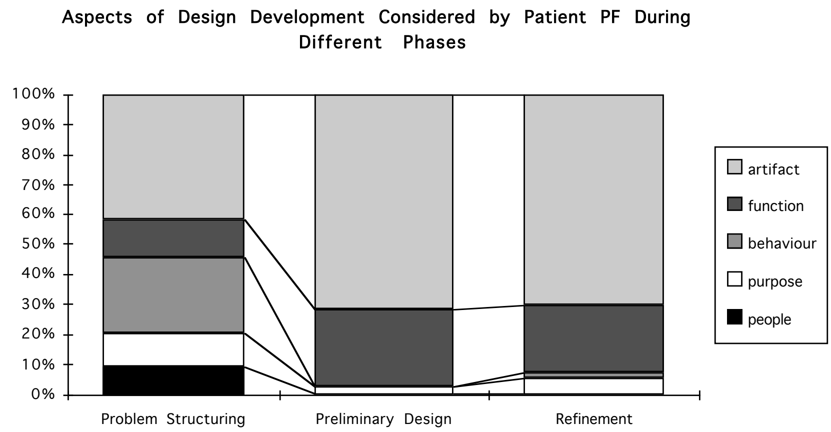

Figure Six: Aspects of design development considered by patient during different phases of problem solving

5. Theories of Frontal Lobe Function

There are several theories of frontal lobe dysfunction in the current literature that try to explain the types of deficits encountered by PF, including somatic markers (Damasio, 1994), structured-event complexes (Grafman, 1989), and supervisory attentional system (Shallice, 1988).

Damasio (1994) argues that the major issue with patients with medial ventral frontal lobe lesions is that they make poor judgments in real-world situations. He also notes that such patients have severe emotional and social problems. They seem detached, unconcerned, and uninvolved. Damasio makes a causal connection between emotional deficits and poor judgment. His intuition is that there must be a close integration of the cognitive and the emotional. He suggests that the cause of patient's poor judgments is that these patients are unable to *inform* cognitive/reasoning processes by visceral, noncognitive, emotional factors, which he calls "somatic markers".

> In short, *somatic markers are a special instance of feelings generated from secondary emotions*. Those emotions and feelings *have been connected, by learning, to predicted future outcomes of certain scenarios.* When a negative somatic marker is juxtaposed to a particular future outcome the combination functions as an alarm bell. When a positive somatic marker is juxtaposed instead, it becomes a beacon of incentive. (Damasio, 1994, p.174)

The structured-event complex (SEC) theory (Grafman, 1989) proposes that much of our world knowledge is stored in script- or episode-like data structures and frontal lobe patients have difficulty in retrieving these structures. Scripts are large-scale knowledge structures that are thought to account for much of our routine behavior. Formally the representations – called managerial knowledge units (MKUs) – are hierarchically ordered, linked list data structures. The theoretical properties include varying thresholds of operations, temporal properties, categorical distinctions, multiple formats of representation, combinatorial binding with other forms of knowledge, and a relational cognitive architecture. The hypothesis is that frontal lobe dysfunction results in an impairment in the ability to access and retrieve these data structures. Its basic prediction is that frontal lobe patients will have more difficulty with knowledge-rich tasks than knowledge-impoverished tasks.

The supervisory attentional system (SAS) theory (Shallice, 1988) tries to account for patients' differential performance in routine and novel tasks by postulating dual control mechanisms. The idea is that there is a built-in contention scheduler that determines responses in over-learned, routine situations. However, when the organism is confronted with a novel situation, the contention scheduler is unable to cope and passes control to the more sophisticated supervisory attentional mechanism. Shallice's claim is that the frontal lobes serve as this meta-level control mechanism.

While there is much to be said for these theories, the problem for our current purposes is that they do not give us any reasons to believe that these mechanisms are differently implicated in the early and later phases of design problem solving. That is, nothing in these theories predicts that patients should have more difficulty in the preliminary design phase than the later more structured phases.

Goel (1995) characterizes design problem solving as involving four development phases: problem structuring, preliminary design, refinement, and detail specification; and notes that each phase differs with respect to the type of information dealt with, the degree of commitment to generated ideas, the level of detail attended to, the number and types of transformations engaged in, and the symbol systems needed to support the different types of information and transformations. This is depicted in Figure 7.

What is of interest to us here is the contrast between preliminary design and refinement and detailing phases. Preliminary design is a classical case of creative, ill-structured problem solving. It is a phase where alternatives are generated and explored. This generation and exploration of alternatives is facilitated by the abstract nature of information being considered, a low degree of commitment to generated ideas, the coarseness of detail, and a large number of lateral transformations. A lateral transformation is one where movement is from one idea to a slightly different idea rather than a more detailed version of the same idea. Lateral transformations are necessary for the *widening of the problem space* and the exploration and development of kernel ideas (Goel, 1995).

The refinement and detailing phases are more constrained and structured. They are phases where commitments are made to a particular solution and propagated through the problem space. They are characterized by the concrete nature of information being considered, a high degree of commitment to generated ideas, attention to detail, and a large number of vertical transformations. A vertical transformation is one where movement is from one idea to a more detailed version of the same idea. It results in a *deepening of the problem space* (Goel, 1995).

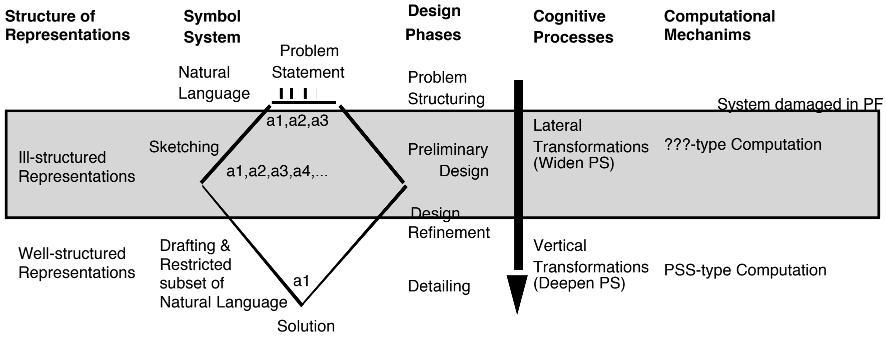

Figure Seven: The design problem space

Figure 7 also notes that preliminary design phases are accompanied by “ill-structured” representations (in this case belonging to the symbol system of sketching), while the refinement and detail phases are accompanied by more “well-structured” representations, belonging to the system of drafting (Goel, 1995). Intuitively one might understand "well-structured" mental states as being precise, distinct, determinate, and unambiguous. “Ill-structured” mental states, on the other hand are imprecise, ambiguous, fluid, amorphous, indeterminate, vague, etc. A formal treatment appears in Goel (1995).

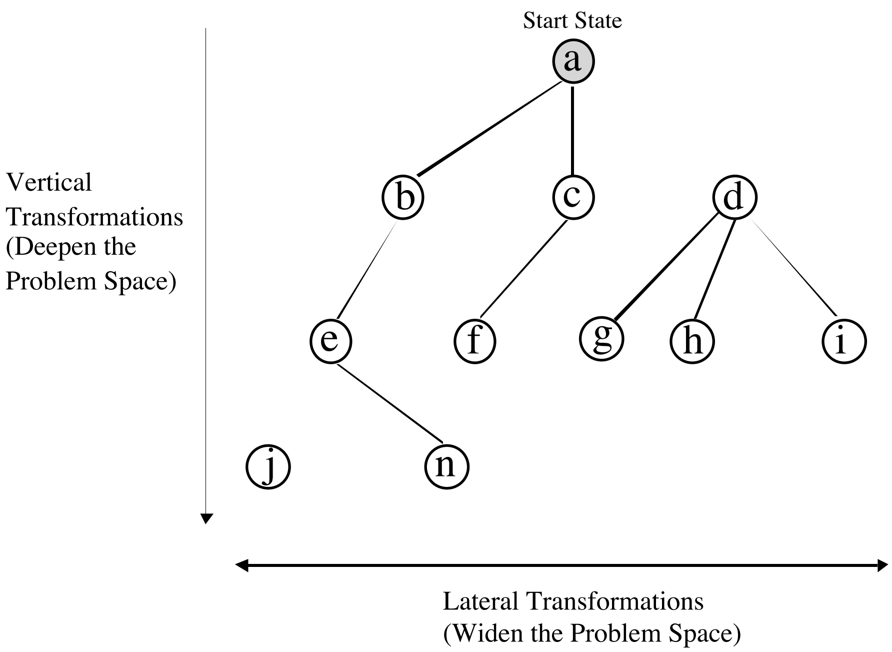

Figure Eight: Structure of state space deemed to be necessary for well-structured problems

Some of these properties of representations are illustrated informally in Figures 8 and 9. Figure 8 shows a well-structured state space and how it is developed in by vertical and lateral transformations. I would like to pick out three properties of this problem space: (i) no state overlaps with any other state; (ii) there is a measurable amount of "distance" between states; (iii) the referent of a state does not change with context (i.e. with where it appears in the graph) so the states are unambiguous.

In contrast to the state space in Figure 8, the state space in Figure 9 is ill-structured. (i) There are overlapping states such as *g* and *h*. (ii) There are "densely" ordered states – with little or no measurable "distance" between them – such as *j* through *m*. (iii) States in such problem spaces can have different referents depending on their location in the graph and are therefore ambiguous.

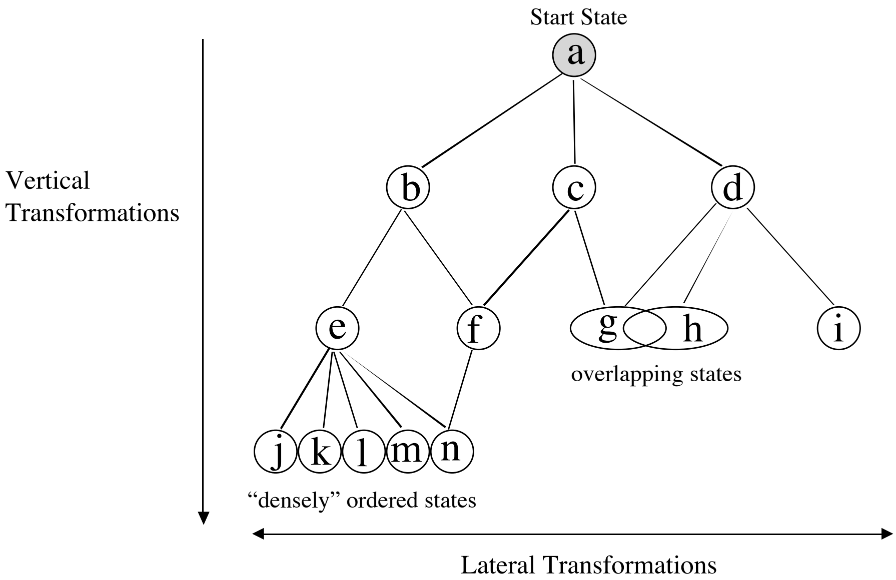

Figure Nine: Structure of state space deemed to be necessary for ill-structured problems

There is empirical evidence that these properties of ill-structured representations facilitate lateral transformations in the following ways (Goel, 1995):

1) The overlapping of states introduces a degree of coarseness into the problem space by allowing a single state to simultaneously instantiate a number of ideas in a noncomplex or primitive manner. The presence of overlapping states allows the problem solver to remain non-committal about the state he/she is in.
2) The dense ordering of states gives the problem space degree of fine-grainedness. This reduction in "distance" between states allows for the coverage of the full range of possibilities and facilitates the transformation from one state to another.
3) The ambiguity of states insures that the referents of the states during the early phases of design are indeterminate. Ambiguity is important because one does not want to crystallize ideas too early and freeze design development.

This is graphically summarized in Figure 10.

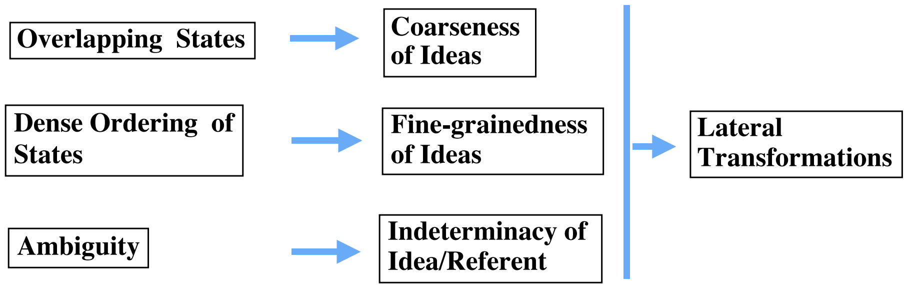

Figure Ten: Role of ill-structured mental states in lateral transformations

I am arguing that the crucial cognitive/computational differences between the phases of planning are to be found in the structure of the representations and computations associated with different planning phases. Well- and ill-structured representational system are needed to underwrite well- and ill-structured planning phases respectively. It can further be demonstrated that ill- and well-structured representations support different types of computational mechanisms (Goel, 1995). Well-structured representations are necessary for the "classical" von Neumann-type computational devices postulated by cognitive science. I have referred to these as PSS-type (Physical Symbol System) computation in Figure 7. Ill-structured representations support computations in different types of systems, perhaps multi-layered connectionist networks. These are referred to as ???-type computation in Figure 7.

Given this theoretical apparatus and the behavioral deficits observed in the patient, we postulate that PF's lesion has resulted in a selective impairment of the neural system that supports "ill-structured" representations and computations (see Figure 7). The theory allows that the "well-structured" representation and computation system may be largely intact and predicts that the patient may be competent at the detailing (well-structured) phase of problem solving where such a system is required. But because his preliminary design phase is unsuccessful, it is hard to make much of later phases. However, his exceptional performance during problem structuring and on the well-structured neuropsychological tests suggests that the computational system used for well-structured tasks may be intact.

The claim about ill- and well-structured representational and computational systems is a general claim about the structural and computational properties of mental states (Goel, 1995). The formal properties differentiating ill-structured and well-structured representations do not break down along linguistic and pictorial lines. So there is no reason to expect that the explanation offered is specific to design or drawing domains, though the system is particularly well developed in designers and they can provide an external trace of it. One would expect to find ill-structured representations and computations used in many ill-structured problem solving domains.

6. Conclusion

I have provided data to suggest that the intuitive/behavioral distinction between Type 1 and Type 2 design knowledge runs deep. It has a neuroanatomical basis. The data suggest that while the explicit Type 1 knowledge may be necessary for successful designing, it is clearly not sufficient. When Type 2 knowledge is absent, patients literally cannot design. Furthermore, I have argued that this "knowledge" is not knowledge in the conventional sense. On my account, Type 2 knowledge consists in having an intact, well developed neural mechanism to deal with "ill-structured" situations. As a mechanism, it is not something to be learned and remembered, like a formula for calculating a point load on a beam. Rather, given the neural endowment, the educational challenge is to develop and hone it through practice. On this account it is not surprising that Type 2 knowledge should seem inarticulate and elusive.

This view has consequences for design education. "Teaching" students Type 2 design knowledge is a matter of giving them the opportunity and encouragement to develop the representational and computational mechanisms necessary to deal with ill-structured situations. The data and arguments I have presented do not speak to *how* such opportunities should be provided. My own personal view is that the best strategy may be to put students in situations that *simulate* the ill-structured, incomplete, and under-constrained nature of real-world design problems and allow them to *grope* their way through (with some minimal guidance). There is, of course, nothing new in this proposal. It just reinforces the importance of traditional design studios. The reason they work so well – and must remain an integral part of design education – is that they provide students with practice in the deployment and development of the relevant neural mechanisms necessary to cope with ill-structured situations.

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