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Frames of Reference in Architectural Design: Analyzing the Hyper-Acclamation (A-h-a-!)

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Frames of Reference in Architectural Design: Analyzing the Hyper-Acclamation (A-h-a-!)

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Abstract

The discovery of a creative solution occasionally corresponds to the sudden attainment of a mental insight. Our purpose is to formally describe this phenomenon and the cognitive mechanisms that lead to it. The approach is based on the replicability of just such an insight which underlies the solution to a well known puzzle: the nine-dot puzzle. The insight coincides with the realization that the problem can only be solved when a spurious constraint is removed. Two experimental results are reported: one on the nine-dot puzzle and the other on an architectural sketch design problem. The sketch design problem was structured with several restricting frames of reference to create a situation analogous to the nine-dot puzzle. Subjects' design behavior was analyzed to identify the mechanisms used in achieving the mental insights which allow designers to go beyond the implicit restrictions of these frames. A general model, called SMI-GI, of the mental insight based design and discovery process is described. This model foresees a computer system that can be used to simulate the mental insight mechanism and consequently lead to the systematic examination of this aspect of design creativity.

1. Creativity and the Sudden Mental Insight

During the late fifties and sixties, as the inventory on design methods was increasing, behaviorist psychology turned its attention to creativity. Conferences and symposia were held, while proceedings, treatises and papers were published. Most of these studies attempted to describe creativity through the stimulus-response paradigms that were dominant at that time.

Relationship of creativity to related phenomena was also explored. These included subjects such as, genius, creative genius, intelligence, originality, talent, divergent thinking, aesthetics, even nervous disorders. The typical approach to this subject is found in studies measuring personality traits (MacKinnon, 1972). These studies report the designers' performance on tests such as the Concept Mastery Test (Terman, 1956), Gottschaldt Figure Test (Crotchfield, 1958), General Information Survey and California Psychological Inventory (Gough, 1954), Allport-Vernon-Lindsay Study of Values (1951), Barron-Welsh Art Scale (1952), and Minnesota Multiphasis Personality Inventory (Hathaway and McKinley, 1945). As implied by the names given to these tests, their results focus on general behavioral tendencies.

Progress has also been made in exploring the notion of creativity through the notion of expertise within a particular domain, such as, chess, music, painting, or poetry, even architecture. There has been considerable development in the methods used to measure chess masters' expertise and the calibration of these methods in the field. One of the most remarkable results of the work started by deGroot (1965) is that the factors which mark expertise in chess have less to do with the ability to “search” but more with the ability to “recognize.” While determining their moves, chess masters do not display superiority in looking ahead many more plies deeper than non-experts. Instead, they display an uncanny ability to recognize relationships between pieces on the chess board that are not as readily apparent to less experienced players (Chase and Simon, 1973; Charness, 1974). A finding that has been an underpinning for most of these studies is the discovery of memory “chunks” by Miller (1956) that explain the basic cognitive mechanisms for knowledge representation in chess and in other domains. The cumulative effect of all of these studies has been to redirect expertise and creativity research into the domain of memory and recognition.

The “time at task” hypothesis, an extension of these early findings, states that in order to acquire expertise in a given area, such as chess, one needs to learn a large number of chunks. Generally, this is in the order of 100,000. Furthermore, the minimum amount of time required to gain this knowledge is considered to be a decade (Hayes, 1985). Studies have been conducted to verify this hypothesis, principally by Hayes (1985, 1989) and Wishbon (1988).

Hayes' work on musical composition, a seminal piece in this area, is based on surveys of some of the most famous classical composers culled from published musical catalogues. He has considered two key questions: when did a particular composer start musical training and when did the compositions by the composer reach the maturity that is normally associated with mastery or expertise? To answer the first question, Hayes found adequate data in biographical sources where it was revealed that in most cases the composers started training formally or experienced some incident revealing their prodigious careers. These were unambiguous events indicating the beginning of the individuals' musical training. In answering the second question, he gathered evidence from several independent sources in order to determine the point in time when mastery was achieved. For example, the issuing of recordings of works listed in *Schwann's Guide* and other publications like it have usually yielded reliable information. In other cases, published opinions of authoritative musical historians were consulted. The results of these two investigations confirm the “time at task” hypothesis indicating that even prodigies spend a minimum of ten years at task before they become masters of their art or true experts.

Similar results have been obtained in the area of painting (Hayes, 1985) and poetry (Wishbon, 1988). Indeed it is difficult to determine the attainment of expertise in poetry, as is the determination of the actual onset of training in both poetry and painting. Nonetheless these researchers were able to develop specific methods to overcome these difficulties and have been able to show results similar to those in the area of musical composition.

There have also been some serious attempts at understanding and describing the design process and the underlying structure of the architect's creativity by way of expertise. These studies go back to the early

1970's when Eastman (1969) conducted his pioneering work with protocol analysis. Subsequently many others have conducted similar studies, such as those by Krauss and Myer (1970), Foz (1973), Henrion (1974), Akin (1978, 1986, 1994), and Eckersley (1988). Also some indirect evidence about creativity has been offered by Akin (1988, 1990) comparing problem solving strategies of expert architects to those of novices.

More recently, important steps have been taken towards modeling creativity in the computer, paving the way for formal models concerning creativity (Gero, *et.al.*, 1993, Maher, *et.al.*, 1993; Rosenman, *et.al.*, 1993). While all of these studies have provided important insights into the nature of the design task and how humans deal with it, no comprehensive theory of creativity has yet emerged and there are still significant gaps in research. On the basis of these and other empirical observations, some of the common points concerning creativity can be summarized as:

- creativity arises under special conditions
- creativity is manifested either through a product or a process
- creativity spans a considerable range of activities and products, from the sciences to the arts to everyday occurrences
- the product of a creative act is novel and unusual in some sense
- it is possible to discern some gradation of creativity among these products and processes, for instance, in terms of their social or lasting value

One can often find considerable agreement about these claims. Yet, their coverage by studies in the field is at best patchy. Little is said, for instance, about how creativity actually works or what, operationally, creativity is. We are interested in several questions related to this issue. What cognitive capabilities underlie the behavior that is commonly known as creativity? And how can one measure and model this behavior? In order to shed some light on these questions, the remainder of this paper will focus on the analysis of a well known phenomenon associated with creativity, commonly recognized as the “aha!” response (Perkins, 1981; John-Steiner, 1987), From here on, this phenomenon will be referred to as *sudden mental insight* (SMI).

2. The Aha! Response or the Sudden Mental Insight (SMI)

The commonly recognized “aha!” response is universally considered as a reference to the moment when a creative flash arrives. Famous examples of this creative flash include the discovery of penicillin by Sir Alexander Fleming and the Greek mathematician and inventor Archimedes’ proclamation of ‘eureka’ after formulating the theory of mass displacing its volume in liquids. While these anecdotes are likely to be exaggerations, they illustrate the sudden onslaught of a new idea. Similar experiences occur even under every day situations, often eliciting the rhetorical question: “why didn’t I think of that before?”

Better documented, anecdotal accounts of creativity reveal a range of interesting issues. For example, Mozart speaks of the special qualities of the condition under which the creative “impulse” arrives.

> *When I am, as it were, completely myself, entirely alone, and of good cheer, say traveling in a carriage, or walking after a good meal, or during the night when I cannot sleep; it is on such occasions that my ideas flow best and most abundantly. Whence and how they come, I know not; nor can I force them. Those pleasures that please me I retain in memory, and am accustomed, as I have been told, to hum them to myself. If I continue in this way it occurs to me how I may turn this or that morsel to account, so as to make a good dish of it, that is to say, agreeably to the rules of counterpoint, to the peculiarities of various instruments, etc.*

In this excerpt (Holmes, 1878), Mozart refers to retaining the memories of the pleasures that come and of mentally nurturing them into a "good dish." It is clear that what arrives and what happens to it next are dependent on each other. There is a readiness for the idea which is suddenly conceived. A similar idea is revealed in Tchaikovsky's statement (Newmarch, 1906) where he speaks of the "soil" being ready or the "disposition of the work" being there.

> *Generally speaking the germ of a future composition comes suddenly and unexpectedly. If the soil is ready* -- *that is to say, if the disposition for work is there* -- *it takes root with extraordinary force and rapidity, and shoots up through the earth, puts forth branches, leaves and, finally, blossoms.*

Both of these accounts confirm, at one level, the *a priori* impressions of the creative process. Yet, there are also new insights suggested. While it is virtually impossible to fully explain a process as complex as creativity by relying just on the metaphors used by Mozart and Tchaikovsky, it is reasonable to infer that what arises so suddenly does not arise from nothing but from the cognitive preparation that anticipates and evokes the idea in the first place. Mozart, in fact speaks about turning the "morsel to account.. agreeably to the rules of counterpoint,. instruments, etc.." There exists a body of knowledge based rules by which the idea must abide. This is neither a surprise nor an obstacle to the composer. If these were not anticipated at the conception of the initial idea, would they have been treated in such a matter of fact way? We argue not. In fact, the creative process is a whole in which the conception of the idea influences and is influenced by the anticipation of subsequent developments. Cognitive tools used in this development must therefore be responsible for the "inspiration" that initiates the creative process, as well.

In formulating an investigation of creativity, it is necessary to recognize that the sudden onset of a creative insight, which has eluded the composer or designer until that moment, is a key step. There is no doubt that the soil upon which this *sudden mental insight* (SMI) germinates has to be properly and pains-takingly prepared. In the case of the creative artist this is a familiar yet laborious process. But once it is complete, the conditions for the onset of the SMI are ready. We are interested in formally characterizing these conditions and the cognitive processes that are responsible for them.

Our approach to this question is inspired by findings in a non-design task, namely the nine-dot puzzle which tends to naturally elicit the SMI. In addition, we designed an experiment in a format similar to that of the nine-dot puzzle in order to study architects' SMI behavior. Now, let us review both experiments.

2.1 The Nine-Dot Puzzle

This is a task which involves manipulations in the visual field based on the regular spacing of nine-dots in a plane (Figure 1.1). The goal is to draw four straight lines so that each dot has a line going through it. Furthermore, the lines must be connected endpoint to endpoint so that no more than two endpoints are unconnected to another line. The solution is given in Figure 1.2.

In order to successfully solve the problem, subjects must realize that they are allowed to extend a line beyond the square shaped area formed by the nine-dots. As obvious as this seems while viewing the puzzle solution (Figure 1.2), most subjects tend to, at first, restrict themselves to the area defined by the dots. Restricting the area in this fashion makes the solution impossible to attain since more than two endpoints lie outside of this area and therefore remain unconnected (Figure 1.3).

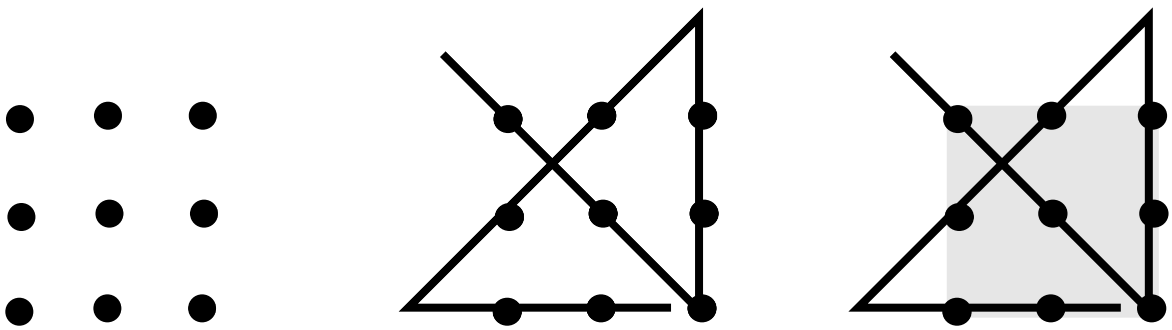

Figure 1.1 Figure 1.2 Figure 1.3

Figure 1.1: The nine-dot puzzle; Figure 1.2: The puzzle solution; Figure 1.3: The restricting frame of reference

Initially, we hypothesized that once this insight is gained, the solution to the problem would become trivial. Our experimental results support the idea that the insight is essential in solving the problem. Furthermore, in most instances its onset is abrupt, thus the term *sudden* mental insight. However, this SMI does not appear to be sufficient in itself, especially when induced externally, to yield the solution. Several other cognitive factors must be present before a solution is guaranteed. In fact, we argue that there is a dependency between these factors and the onset of the SMI.

2.1.1 Methods of the Nine-Dot Experiment

A total of nine subjects participated in the experiment. In the first stage of the experiment, subjects were read a standardized set of instructions explaining the task. “Think aloud” protocols were collected and analyzed (Ericsson *et.al.*, 1980). If subjects were still unable to find the solution, after working on the problem for some time, the second stage was put into effect. This consisted of presenting new instructions stating that the subjects “may place additional dots on the page if it aids [them] in finding the solution.”

2.1.2 Results of the Nine-Dot Experiment

Three of the subjects were able to solve the problem under the first condition. For these subjects, the mean number of trials needed in order to attain the solution was 6.7, while the mean number of trials needed to begin the practice of drawing lines beyond the ‘box’ (i.e., the square shaped area) was 5.4. This certainly supported the conjecture that once the ‘box’ constraint was lifted, the solution became trivial.

On the other hand, three different subjects were not able to lift the restrictive *frame of reference* (FR) implied by the box until quite late in the experiment. Their mean number of trials before solution was 54.3, which is ten times greater than that of the first set of subjects. Only .08% of their trials involved operations outside of the box. One subject in this set engaged in an exhaustive search within the box, trying different shapes, letters and numbers. Only after the introduction of the second stage of the experiment did this subject draw lines outside of the box and was able to reach the solution. Another subject in this set was able to go beyond the FR after the 19th trial, prior to which time he engaged in a somewhat exhaustive search. The third subject, as was the case for the other two in this set, was not able to reach the solution prior to the second stage. In all three cases, the lifting of the FR did not make the solution trivial. That is, although these subjects were able to lift the constraint, they were still unable to solve the problem with ease.

The remaining three, out of the nine subjects, were not able to solve the puzzle even after the implementation of the second stage. These sessions were stopped after subjects were allowed as much time as they wanted before they gave up, which ranged between 1 to 2 hours.

2.1.3 Discussion of the Nine-Dot Puzzle

Contrary to our original hypothesis, several operations in addition to the one that allows the drawing of lines outside of the box, are needed in order to solve the nine-dot puzzle. These include the ability to create new vertices outside of the box (Figure 2.1), and the ability to align these vertices with the remaining dots (Figure 2.2). The three subjects who were able to solve the problem used all three operators. While these operators eluded the remaining six subjects or else they acquired it with much difficulty.

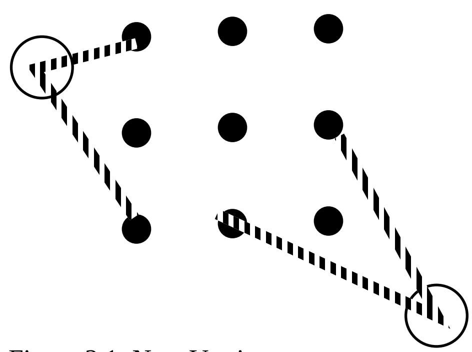

Figure 2.1: New Vertices

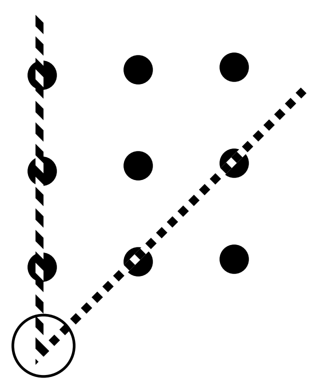

Figure 2.2: Alignment of Vertices

Instructions of the first stage provided the subjects with the idea of correct alignment of the dots, at least within the box. This illustrated the alignment principle, albeit in a simplified form. The second stage provided for the subjects both the operation of creating vertices outside of the box and being able to draw lines through them. All of these operations, including the adaptation of the alignment operation to the outside of the box, were discovered without help by the first set of subjects, those who solved the problem in the first stage. These operations also developed in the second set of subjects, but only after the initiation of the second stage of the experiment. On the other hand, the alignment operation presented an insurmountable problem for the third set of subjects who could not solve the problem at all.

In conclusion, while *breaking out*[1] of the FR (i.e., the "box") appears to be a necessary condition for solving the nine-dot puzzle, it is not a sufficient condition. It also appears to be necessary that a new set of operations, including those of *vertex creation* and *alignment*, be present. Only when all of these operations were simultaneously present did the solution to the puzzle become feasible. Further, the proper functioning of these operations depended upon one another and they had to be acquired in synchrony. Subjects furnished with each one independently of the others did not always succeed in solving the puzzle.

These results point to the conclusion that simply breaking out of an FR is not sufficient to reach an SMI. A new FR must be, simultaneously, established. The new FR needs to have sufficient structure to enable the generation of potential solutions but not so much structure that it prohibits the attaining of the solution as had been the case in the earlier FRs. For the nine-dot puzzle, the structure of the new FR simply has to do with connecting of procedural skills -- forming vertices and alignments -- with the rationale of going outside of the box.

Next, the validity of the general form of this conclusion will be explored in the case of architectural design.

2.2 The Façade Design Problem

A simple sketch design problem was developed in order to replicate a structure similar to the SMI phenomenon observed in the case of the nine-dot puzzle. The problem involved the design of a *façade* (an elevation) for a given partial floor plan of an office suite containing five functions: reception, secretary, conference, staff engineers and chief engineer (Figure 3.1). There is an obvious set of moves that will yield a rather mundane façade for this floor plan. We hypothesize that this unsatisfactory solution is obtained by following directly from the information given and simply indicating four windows aligned with the marks on the floor plan (Figure 3.2).

The façade design in Figure 3.2 is what is expected when the designers stay within the restricting FRs of the problem. In other words, no SMI is attained that goes beyond these FRs. These FRs are analogous to the box created in the nine-dot puzzle and are defined along five constraint categories: 1) the size, proportion, location of the windows, 2) the number of stories of the building, 3) the construction of the wall, 4) the height of each floor, and 5) the plan organization of rooms. **[1]**

Our hypothesis is that, unless these FRs are *broken out* of, a creative façade design cannot be obtained. Based on the findings of the nine-dot puzzle which is similar in structure to the sketch problem, an SMI shall arise in conjunction with specific design knowledge that is applicable to these FRs' dimen-

1. This term is used, through out this paper, to refer to the intentional violation of the constraint sets represented by FRs.

sions. More specifically, realizing the creative breakthrough should involve both the didactic principle of the SMI (the need to go beyond each restricting FR) *and* other procedural knowledge necessary for applying this principle to the case at hand (aligning windows, extending the eaves, balancing the mass, and so on -- that is, establishing new FRs).

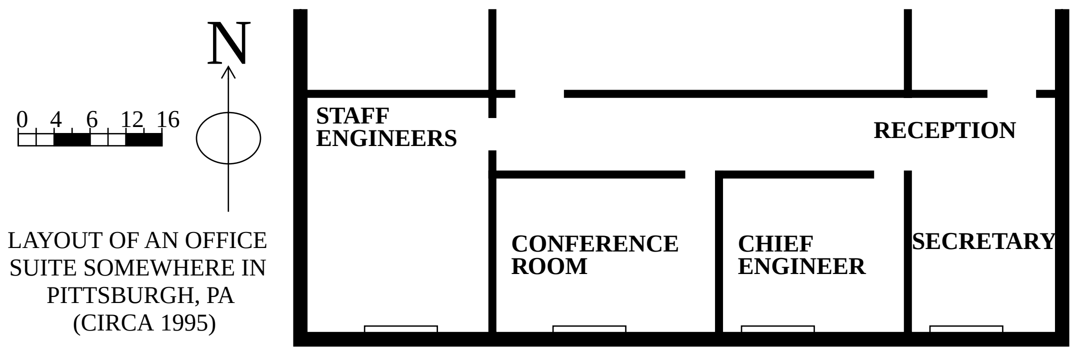

Figure 3.1: Stimulus used in the sketch design problem.

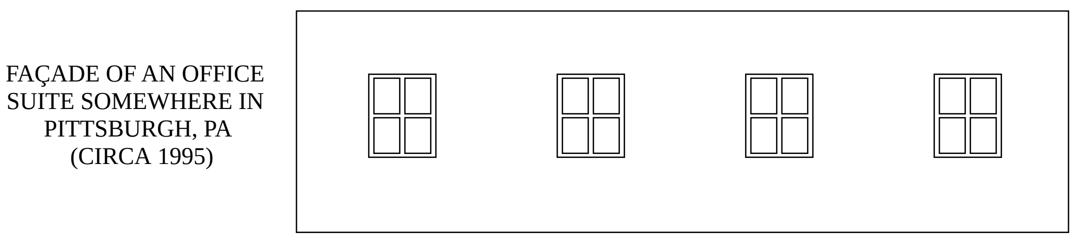

Figure 3.2: Façade design derived directly from the problem statement, which does not represent a creative solution.

Our hypothesis is that, unless these restrictions are *broken out* of, a creative façade design cannot be obtained. Based on the findings of the nine-dot puzzle which is similar in structure to the sketch problem, an SMI arises in conjunction with specific design knowledge that is applicable to these FRs' dimensions. More specifically, realizing the creative breakthrough should involve both the didactic principle of the SMI (the need to go beyond each restricting FR) *and* other procedural knowledge necessary for applying this principle to the case at hand (aligning windows, extending the eaves, balancing the mass, and so on).

The items in list [1] are an illustration of the conditions that may be sufficient to define a *trigger set* for the SMI. In addition, certain strategies may be available to the expert designer which would actually trigger the SMI: 1) exhausting all alternative solutions within the given FR (as many subjects in the nine-dot puzzle did by trying different shapes, letters and numbers), 2) trying a domain independent heuristic rule to leap out of the existing solution cycle (for example: inverting the relationship of design elements like rooms and floors or flipping over entire plan layouts), 3) redefining the FR based on domain knowledge (for example: aligning and balancing of elements rather than their strict symmetrical composition), and 4) using heuristics to realize a breakout from an FR (for example: recognition of a new visual pattern). **[2]**

Formulated in this way and based on the insights gained in the nine-dot experiment, the SMI should function as a tool for creativity only if FR breakouts come with a set of relevant *procedures*. Further, these procedures should be explicitly available to the designer. Externally supplied hints covering only a part of this knowledge, for example the didactic part, would not be sufficient to trigger an SMI. In fact, even with such hints, designers would be forced to figure out additional procedures that can help them with breakouts. In the case of the non-expert, however, this would to be *un*likely.

2.2.1 Methods of the Sketch Design Experiment

A total of eight subjects participated in the study: four experts and four novices. Two were part of a pilot intended to test the experimental design. All subjects were given the following instructions:

> *The client has asked you to design the South façade for the office suite given above. The client is interested in considering some of your design ideas before proceeding with anything else. You have roughly half an hour to develop your ideas for presentation. Please use the attached sheets and sketching medium to undertake all of your work. Please make sure that, for the benefit of the experiment being conducted, you 'think aloud' as you do your work.*

The instructions were slightly altered for the "novice" condition, so that the architectural terms would not confuse them. Subjects were provided with a complete set of sketching material. A video camera was placed in front of the subjects so that both their motor and verbal protocols could be recorded. Upon completion of the design task, subjects were given a brief questionnaire regarding the five FR categories in [1].

2.2.2 Results of the Sketch Design Experiment

The protocols of the subjects were transcribed and segmented by two independent experimenters using verification techniques recommended for protocol analysis (Ericsson *et.al.*, 1980). The results reported here are principally based on the analysis of the pilot data and some interim results from the other subjects' protocols. On the average the length of the design session was about 35 minutes, with the designers spending 36 minutes and the non-designers 33 minutes to complete the given task. A sample of designs developed by two subjects, one a designer and the other a non-designer, are included in Figures 4.1 and 4.2, respectively.

2.2.3 Analysis of the Sketch Design Experiment

Our analysis intends to uncover whether our assumptions about SMI and FR are valid for the sketch design problem; and which of the five triggers listed in [1] and the four strategies listed in [2] were applied by the subjects; and if none were, then what trigger the SMI? This was accomplished in several steps: 1) identify the FRs used in the formulation of problems by subjects, 2) identify the breakouts from these FRs, and 3) show how these breakouts correspond to SMI. The sketch design problem was analyzed by examining the FRs adopted or used by the subjects. Some of these FRs existed in the experiment instructions. Others were developed by the subjects. In the case of Subject-1 there were five of these:[2]

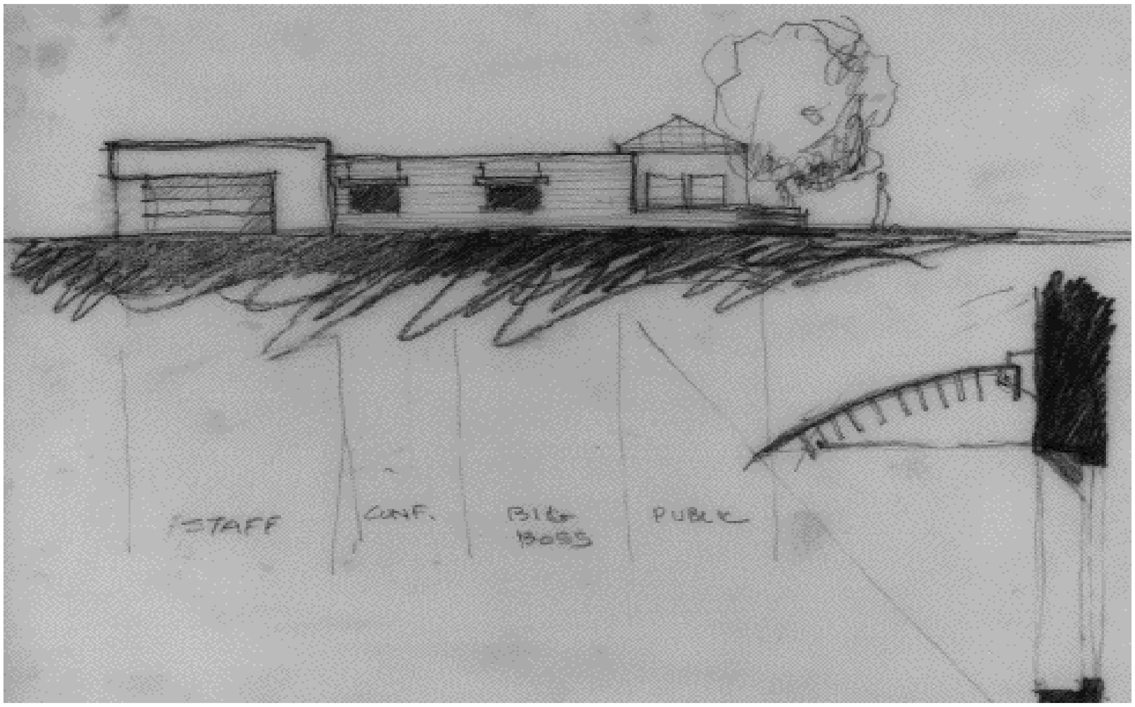

Figure 4.1: Design developed by Subject-1.

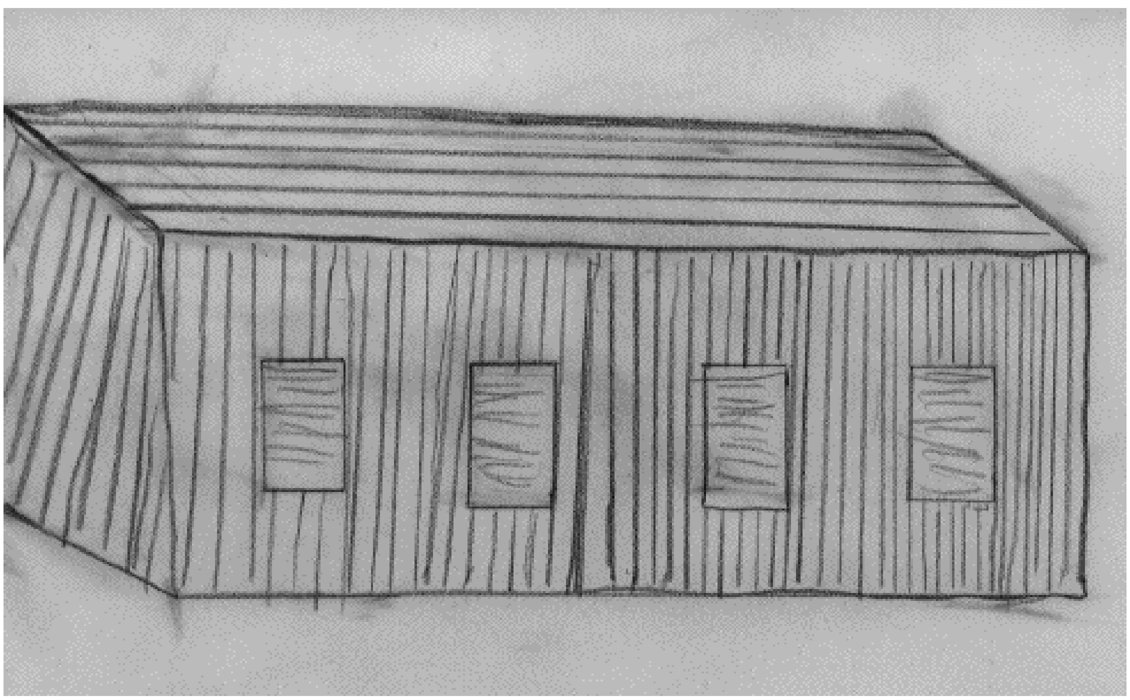

Figure 4.2: Design developed by Subject-2.

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2. The notation referring to the FRs is as follows: the first number following the letters “FR” designate the *subject*, the next number after the hyphen is the *identification* of the FR itself, and if any other numbers follow after a period, these designate the *versions* of the FR.

FR1-1:= window geometry; *source*: given plan; *ref.*: "repeated windows"

FR1-2:= ceiling height; *source*: assumed standard; *ref.*: "12 ft. ceiling height"

FR1-3.1:= being located at ground floor; *source*: statement; *ref.*: "on ground floor"

FR1-3.2:= part of a single story building; *source*: implicit assumption; *ref.* see FR1-3.1

FR1-4:= relief from the planar surface of the façade; *source*: implicit assumption; *ref.*: "which gives some relief"

FR1-5:= materials used in constructing the façade; *source*: implicit assumption; *ref.*: "texture and contrast to the material" **[3]**

Subject-1 drove the first three FRs from the information given in the problem statement. After these FRs were established, he deliberately spoke about the need to break out of these FRs using explicit design moves. For example, in the case of FR1-1, Subject-1 referred to the existing window geometry as "repetition" and "deadening." He also spoke about specific design operations, such as, infusing "variety," "hierarchy" and various "grouping" strategies, in order to fix them. The last three FRs in [3], one of which is a sub-set of FR1-3.1, were stated only implicitly. The subject mentioned them neither prior to breaking out from them nor at the time he made the breaking out move. Their relevance was decided based on two sources of evidence: 1) the subject explicitly spoke about these FRs elsewhere in the protocol (i.e., material selection, multistory arrangement, and thickness of the South wall), and 2) in response to the post-interview questionnaire, he stated explicitly that these issues were addressed.

In the case of Subject-2 a smaller number of FRs were observed, which were a proper subset of [3]:

FR2-1 := size of windows; *source*: from given plan; *ref.*: "want to make [these] window[s] bigger"

FR2-2 := access door; *source*: from given plan; *ref.*: "don't see any doors."

FR2-3 := ceiling envelope and roof form; *source*: statement; *ref.*: "nice big curvy ceiling like roof"

FR2-4 := materials selection; *source*: statement; *ref.*: "maybe [the wall] could be brick." **[4]**

While there are many similarities between the two FR sets, the designs produced by each subject are significantly different. Note, for instance, how the non-designer's solution (Figure 4.1) is anticipated by the normative solution (Figure 3.2) as opposed to how different the designer's solution (Figure 4.2) is from both of these. In order to explain these differences, the manner in which these subjects explicitly broke out of the FRs, while realizing their design innovations, was considered.

Starting with the very first FR established in reference to the regularity of the window openings, Subject-1 systematically breaks out of each and every FR in [3]. The issue of window openings is also the very first one entered in the subject's notes. This is not surprising as façade design, more often than not, hinges upon the placement and proportions of windows. Once this breakout is accomplished, it is followed by a series of breakouts from remaining FRs.

Another approach illustrated in Subject-1's protocol is the "piggy-backing" of all of the subsequent breakouts on the design issue represented by the first breakout. Subject-1 makes four design sketches addressing these issues: West to East ordering of the windows, relief elements on the façade, the roof forms, and material selections of the wall construction (Figures 5.1, 5.2, 5.3, and 5.4 respectively). Each sketch elaborates an *original* design breakout. This process is carried out methodically undertaking the integration of all subsequent solutions with this one.

Window proportions are also one of the first FRs out of which Subject-2 tries to break. She remarks “I mean if you’re looking in, I don’t know that I would necessarily see anything. If I stand outside all I pretty much see is windows... right?” Similar to Subject-1’s piggy-backing strategy, Subject-2 also chooses one breakout category as a principal one: construction materials. This becomes the thread that connects all subsequent breakouts.

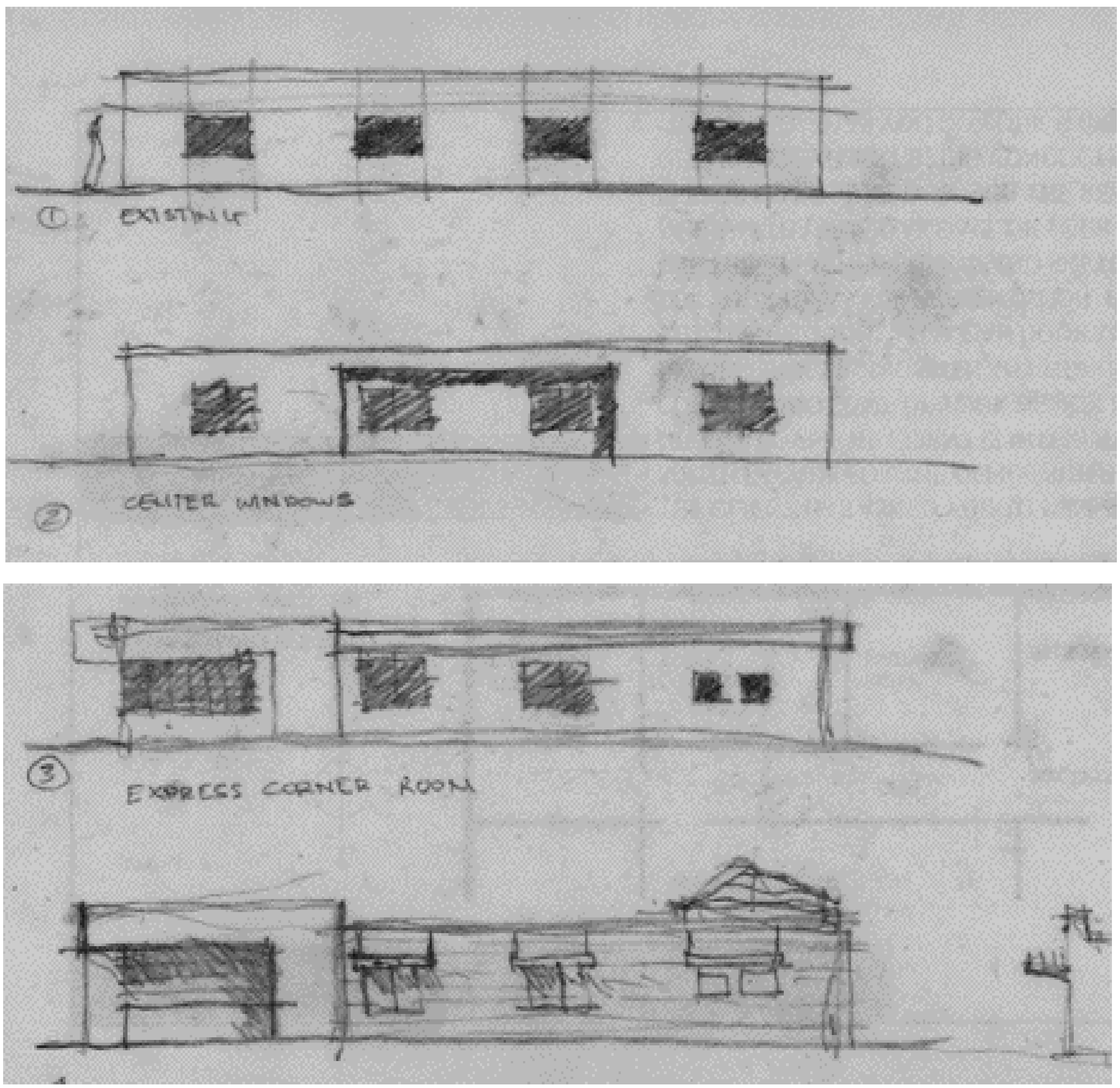

Figure 5: Sketches done by Subject-1. 5.1: “Existing,” 5.2: “Center windows,” 5.3: “Express corner room,” 5.4: Final version.

The resulting design in the case of Subject-1, as expected, goes much further than that of Subject-2, especially in developing a formal hierarchy and integration of forms and materials. Subject-2's solution represents the standard solution to the problem, preserving almost all of the FRs that are implied or stated in the problem statement. There are two minor deviations from this: adjusting the sill height of the center windows and applying a roof structure. Subject-1 on the other hand creates a whole new façade with unique features.

The difference between the two subjects seems to arise from the same phenomenon observed in the nine-dot puzzle: recognizing the need to breakout of the FRs is not sufficient to reach a creative solution. One also needs the procedural knowledge that is necessary to actually implement each breakout. In the case of Subject-2, due to a lack of training in design, this procedural knowledge appears to be unavailable.

2.2.4 Conclusions: SMI and Creativity in Design

The results outlined above have led us to develop several working hypotheses about creativity. Problems that require a level of creativity, such as design, are often restricted through *frames of reference* (FRs). Realizing a creative solution, by breaking out of an FR, depends on simultaneously specifying a new set of FRs that restructure the problem in such a way that the creative process is enhanced. The new FRs must, at a minimum, specify an appropriate *representational* medium (permitting the explorations needed to go beyond those of the earlier FRs), a design *goal* (one that goes beyond those achievable within the earlier FRs), and a set of *procedures* consistent with the representation domain and the goals.

The ability of designers to find the right set of FRs to violate, opens up the possibility of *sudden mental insight* (SMI). On the other hand, the definition of new FRs actually can realize the SMI. This step involves both *declarative* and *procedural* knowledge (Neves and Anderson, 1981) to be a part of the FR specifications. In the experiment described above, for example, when the declarative form of knowledge was supplied by experimenters, some of the subjects were still unable to realize an SMI. A possible explanation for this is that the inexperienced designers do not posses the requisite domain knowledge to determine how to construct new FRs that have the greatest potential to lead to new and unique solutions.

It is also important to note that there are differences in the roles that these FRs play in puzzle-like problems *versus* in architectural design. In the former case, successful solutions need to strictly adhere to some of the FRs, the violation of which render the problem unsolvable.[3] In the latter case, it is less likely that such infeasible solutions, i.e., gravity defying structures, inaccessible spaces, etc., are detrimental to the exploration of a creative solution. Proposals by notable architects, such as the expansive cantilevers of Fallingwater by F. L. Wright, or the abrupt termination of stairs that run into blank walls by P. Eisenman, are considered creative design inventions.[4]

3. In another, informal experiment, it was observed that elementary school students found such "unacceptable solutions" to the nine-dot puzzle that violated the rules of the puzzle. One child proposed a single thick line across the entire field of nine dots, while another proposed folding the paper on which the nine dots are placed so that three sets of three dots coincide and then drawing a single line across this set. These approached are indeed creative in redefining the puzzle but in the process of doing so they trivialize the finding of the solution. In this sense, they resemble a design problem more closely, but offer very little in the way of explaining the SMI for *solving* the puzzle.

3. Computational Modeling of Creativity

The field of creativity research has somewhat of a checkered past. The various approaches reviewed at the outset illustrate a diverse set of motivations, goals and methods. The goals that motivate us here have to do with describing and predicting specific aspects of creativity, using *information processing models*.

Some consider such an approach to be inherently flawed, especially those in the fields of art and creative production. They argue that creativity, by definition, is spontaneous, unpredictable and eludes scientific and formal representation. They argue that the very process of codifying it takes away its spontaneity and ultimately yields a formalism that misses the entire point of the creative act. Particularly, if one generates creative products with the aid of the computer, then the cultural yard stick used to measure creative value will rapidly shrink. Even as these cultural and "philosophical" difficulties are acknowledged, the process of formalization must commence. This approach can only enhance our understanding of creativity even if it ends up brining it down to earth, so to speak. In fact, this would be a welcome process of de-mystification that can make the *wonder* of creativity clearer to the naked eye.

Our intent, then, is predicated on the value of modeling design creativity in the computer. An inherent danger in this task is the confusing of the dual motives of this modeling process: using computers to model creative products *versus* using computers to better understand creativity (Flemming, 1996). Our proposal is directed towards the latter, which requires that these motives are kept distinct. This is why so much attention has been paid to the descriptive aspects of the phenomenon, in the earlier sections. Once a mature and robust understanding of the phenomenon becomes available, the time will be right for developing creativity assistance tools for design.

3.1 The SMI Generator-Interpreter (SMI-GI)

The conceptual model offered here follows along the lines of simulating some of the key ingredients related to the aha!-response: the sudden mental insight (SMI) and the restricting frame of reference (FR). Through these mechanisms we aim to observe and understand the creative flashes of design.

The SMI generator-interpreter (SMI-GI) is made up of four modules: 1) alternative solutions module (AM), 2) problem formulation module (PM), 3) interpreter module (IM), and 4) generator module (GM) (Figure 6). The first two of these, AM and PM are representational modules. AM represents the solutions generated, typically, as outcomes of FR violations; and PM the design problem in hand. The next two modules, IM and GM, are procedural modules that perform critical functions in the simulation of the SMI process: IM infers new problem formulations based on the alternative solutions generated. It does this by identifying FR breakout candidates. GM generates new designs that correspond to these FR breakouts, using specific procedures of design: generation and evaluation.

4. While, in reality, these are non-gravity-defying or non-access-limiting designs, respectively, they certainly exploit those ideas and present solutions that imply them. Thus the exploration of creative puzzle solutions differ fundamentally from the same in design.

It is important to note that SMI-GI as described here is not implemented in the computer, yet. This will be done during future stage of our work.[5] It is also important to restate here that SMI-GI, once implemented will serve as a tool to explore and experiment with the SMI phenomenon, and not replicate any aspects of the design process. Our purpose is to study human creativity and not to try to replicate creative products.

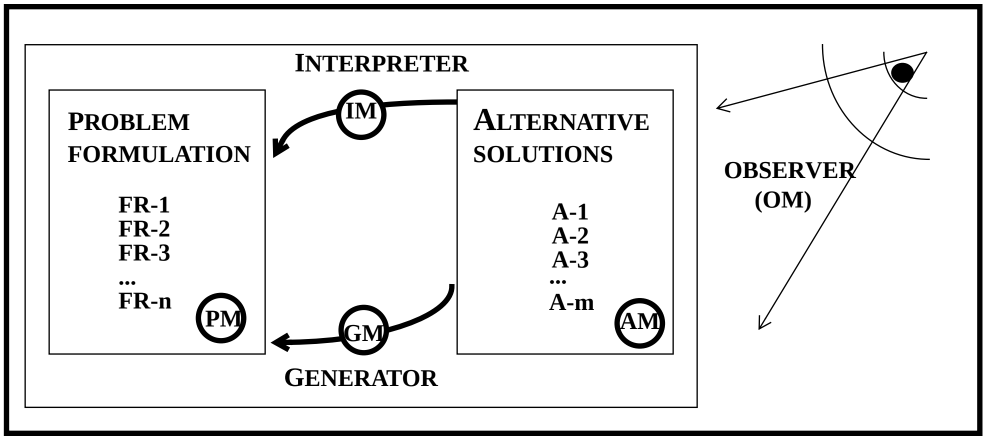

Figure 6: A process model of the SMI Generator-Interpreter (SMI-GI)

3.2 Alternative Solutions Module (AM)

This module is the principal medium of representation of designs in SMI-GI. It codifies, in particular, the design solutions developed in response to FRs both in conformance to and in violation of them -- i.e., the breakouts. Once a breakout strategy is identified in the problem formulation module (next section), design goals related to this strategy will be carried out by the designer using AM.

This functionality will be developed by linking SMI-GI with an *intelligent* CAD system. This system should help in classifying design actions and representations that make the management of FRs and implementation of SMIs easier. For example, to break out of restricting window dimensions and locations, the designer needs to redefine these attributes, parametrically, Furthermore, these acts of redefinition need to be encoded for future reference. They also need to be related to the broken FRs and solutions generated as a result of these breakouts. All of this information needs to be stored in an appropriate form, such as, cases in a case base (Rosenman, *et.al.*, 1993) to facilitate access and reuse of break out strategies. Since in the course of managing a large number of FRs, a large search space will be developed, a robust navigation tool is also necessary (Chien, *et.al.*, 1996). Furthermore a comprehensive design ‘versioning’ capability would make such a sophisticated navigation approach feasible (Akin, 1995).

For obvious reasons, these goals can best be supported in a CAD environment developed on top of an object oriented representation. The CAD system which has all of these features and which we intend to use

5. A multi-year proposal has been submitted to the National Science Foundation, USA.

for SMI-GI is called A Software Environment to Support the Early Stages of Building Design (SEED, Flemming, *et.al*, 1995). The true challenge that waits us is to figure out how to creatively combine SEED and the modules of SMI-GI, especially AM.

3.3 Problem Formulation Module (PM)

Simply put, this module supports a relational network of design elements and their attributes placed on top of AM's representation. Its purpose is to keep a record of current and past formulations of design problems in terms of FRs. At a minimum, the representation of an FR will consist of *aspects* of designs (for example, window dimensions), *goals* to achieve within each aspect (for example, establish a rhythm on the façade using window dimensions), *methods* or procedures for achieving these goals (for example, apply the *Modulor* system of Le Corbusier) and a robust *representation* mechanism. PM would be designed to contain corpus of *aspects*, *goals* and *methods*. By associating these in particular ways, the designer will be able to represent existing FRs as well as new ones that would be needed to replace the violated ones.

As observed in the earlier sections, some FRs are given in the problem statement (for example, wall thicknesses, equal window bays, etc.). Other FRs are either inferred by the subjects from given information or just from general knowledge (for example, single storey building, etc.). It is important that these are represented in PM under different categories. Two orthogonal taxonomies can be used for this purpose: implicit *vs.* explicit, and problem based *vs.* designer based FRs. These distinctions are particularly important for the functions of the generator module (GM).

Since FRs that are defined in order to realize SMIs are potentially open ended, this module must provide the capability for the user to define and redefine FRs on the fly. This presents further formal and computational challenges. The problem is not just to be able to declare new associations between known entities using known properties such as on HeGeL (Akin, 1987), but to declare new entities and even new properties dynamically. Thus PM will need to allow new types and classes to be declared; as well as providing assistance to the user to identify these classes and relate them to existing ones.

3.4 Interpreter Module (IM)

Simply stated, this module is an expert system for semantic inference making. An earlier example of such a system ca be found in AIM (Akin 1978). IM examines the contents of PM and develops hypotheses about which FRs should be violated. This in turn constitutes the "advice" on the basis of which the SMI can be developed. For example, if an equal spacing or positioning of windows is observed, a breakout from this FR may be recommended. Similarly, if wall sections show no variation between interior and exterior partitions a range of construction technologies may be suggested. IM's principal role is to detect noteworthy patterns in the FR representation and the potential breakouts from these FRs. This process serves as the trigger for SMI.

Several aspects of our protocol analysis results are relevant for the design of IM. One is the result that inducing SMI by declarative information alone is not enough. Subjects who cannot link this kind of declarative information with the corresponding procedural one, do not seem to benefit from the SMI. Thus any advice developed by IM has to be accomplished with procedural information. This is why an expert system approach is preferred over others. Through an expert systems appropriate methods can be coupled with appropriate goals and attributes to form FRs. Another approach is to develop graphic output capabilities in IM. Since designers seem to find most of their SMI inspiration in the visual domain, even simplistic recommendations presented graphically can lead to important design breakthroughs.

A way of implementing IM is to assemble a repertory of design operations which can be used to successfully breakout of FRs. These can be represented in the form of a *rule-base* (Mitchell, 1990) utilizing heuristic reasoning methods (Hunt, 1974; Winston, 1984) to match the state of the design problem with appropriate breakout strategies. There may be domain independent heuristics, such as item 2 in [2], or domain dependent ones, such as item 3 in [2] included in such a rule-base.

The potentially interesting aspect of IM is that its suggestions that are intended to lead to SMI can be as unexpected as those that are observed in human protocols. The challenge, of course, is to build a robust expert system that can recommend appropriate SMI strategies. Furthermore, if the SMI behavior is indeed to lead to creativity, then the rule set of IM must also be dynamically defined. This requires that a grammar interpreter be available. Several current efforts in this direction are noted by us (Krishnamurti and Stouffs, 1993). The implementation of this aspect of SMI-GI remains to be our greatest challenge.

3.5 Generator Module (GM)

This is a key component of SMI-GI which is responsible for the building, modifying and otherwise maintaining of the alternative design solutions based upon the newly established FRs. This can be accomplished by applying to the problem the methods and representations of the new FRs: checking the conformance of alternative solutions to the FRs and keeping track of any violations in the proposed solutions. Through this process, GM can provide feedback to PM in order to evaluate FRs in their potential to lead to creative solutions. Several strategies can be used, based on stochastic methods to analyze the data, concerning success in creating new solutions. Here, heuristic rules may also be used to help the designer recognize creative or unusual solutions.

As these four components (AM, PM, IM, and GM) are place in an interactive context, methods will be established for systematically observing what is transpiring and for drawing conclusions about how well the behavior of subjects verify our hypotheses or how this explains creative design behavior. In particular the hypotheses regarding SMI will become more robust and central to the study of creativity in design. This is shown as the OM functionality in Figure 6.

4. Summary

Two experiments examining a cognitive phenomenon called the sudden mental insight (SMI) have been presented. The results explain some instances of the commonly known Aha!-response. In the case of the nine-dot puzzle and a sketch design problem, the process of the onset of the SMI has been described. The setting of frames of reference (FRs) either by the problem or by subjects, and more importantly how these are broken out of in realizing the SMI are the key ingredients of this process.

In the nine-dot task, contrary to popular belief, the inducing of an SMI appears to be a non-trivial matter. Declarative information about which FRs need to be violated is not sufficient to induce the SMI. Rather, related procedural knowledge appears to be essential for this. This type of knowledge seems to be available when subjects discover the key breakout patterns on their own. In design, skills and knowledge in the visual composition and construction domains also appear to be essential in carrying out successful breakout strategies.

Based on these results the features of an operational model called SMI-GI has been proposed. This is not intended for the automatic generation of creative designs; rather, it will assist the user to identify new SMI strategies based on the analysis of the problem and the FRs which constrain the design problem. There are four sets of benefits that can be drawn from this model.

First, by observing the correlation between the IM, the FRs established in PM and the alternative solutions created in AM, we expect to determine how creative flashes can be induced. It is plausible that there may be other factors that help in their induction. If the proposed correlations do not hold, these factors should be evident in the results obtained. This approach will give us new insights about what other factors of creativity are plausible in design.

Second, we expect to gain further insights into the relationships between FRs and SMIs. The presently unexplained aspects of this work are the triggers for SMI which are related to the priorities attached to FRs. Designers use alternative solutions generated as stepping stones to formulate new and better solutions. Once adequate data is gathered, based on the observations of SMI-GI, this model will be implemented in the computer, with particular emphasis on the modules: IM and GM.

Third, another specific item of study for us will be the relationship between declarative and procedural knowledge and their potential relationship to induction of SMI. Different combinations of such knowledge in SMI-GI will be simulated. Their impact on the creative process will be observed. For example, by providing only procedural knowledge, only declarative knowledge or a combination of these two, it will be possible to see which one of these is best suited to induce design breakthroughs and SMI.

Fourth, we are interested in the inductive role of the visual domain in all of this. This is a key in understanding SMI. This assertion will be explored by isolating the effects of manual and automated ‘skill’ in inducing creative solutions using different media: CAD-based, manual, hybrid, designer based, or a team of designer and draughtsman based.

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