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EXPERTISE IN THE COMPREHENSION OF ARCHITECTURAL PLANS: KNOWLEDGE ACQUISITION AND INFERENCE-MAKING

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Abstract. The primary objective of this research was to characterize the knowledge acquisition processes employed in abstracting information from the plans, as well as evaluating subjects' resulting conceptual representations of the building. The second objective was to characterize differences due to expertise on both the knowledge acquisition processes used to acquire information from the plans and differences in the resulting conceptual representations of the building. Two types of protocol analyses were conducted on subjects' think aloud protocols to investigate their knowledge acquisition processes: 1) the frequency of systematic (versus haphazard) moves, and 2) the frequency of 3-dimensional search directed across the various plans. Four comprehension measures were developed to characterize subjects' resulting conceptual representations of the building: 1) 2-dimensional comprehension (information directly depicted in the plans), 2) 3-dimensional comprehension (how the building appears in 3-dimensions), 3) building knowledge (conceptual knowledge reflecting the building's style, era, influencing architects, etc.) and, 4) modern design knowledge (conceptual knowledge reflecting aspects of modern architectural design which were used in the building). Experts were found to differ from novices in that they were more systematic in their search processes to acquire information from the plans. Experts' understanding of the plans used to depict the building (i.e., 2-dimensional comprehension) and their understanding of the building as a 3-dimensional entity were much richer than these representations for novices. In addition, experts' understanding of the building's architectural genre was superior to that of novices.

1. Introduction

This research investigates the nature of the cognitive processes involved in the comprehension of graphic information sources and subsequent inference-making in the domain of architecture. Architecture is a particularly relevant domain to investigate the comprehension of graphic information for many reasons: (a) graphics are the primary medium of communication used; (b) the domain has both a conventionalized language and symbol system which facilitates coding the think aloud protocols that are generated in response to the architectural plans, and (c) generating verbal descriptions about buildings is an integral part of the domain i.e., in discussing plans with colleagues and clients (Akin, Dave, & Pithavadian, 1987).

These three features allow for ecological validity. As well, the understanding of architectural plans is a complex, highly specialized, and non-trivial comprehension task since: (a) comprehension of these graphics involves acquiring knowledge of many different types of information, including descriptive or semantic and visual/spatial characteristics (Akin, 1979, 1986; Gobert, 1989; Gobert & Frederiksen, 1988, 1989), and as such is a high level comprehension task, unlike the comprehension of simpler iconic visual representations; (b) understanding a building as a 3-dimensional entity from its plans which are 2-dimensional requires inference-making on information depicted by various line weights and notations; and (c) in the case of multi-leveled buildings, understanding a building from its plans requires a learner to search and integrate information from each of the plans used to depict each of the floors.

As an illustrative example of the required processing employed to understand a building from its plans, the building used in the present study is a modern building called House II designed by Peter Eisenman. It is a 3 story building, there are 3 plans, i.e., horizontal slices, used to depict the building. Plans depict buildings horizontally floor by floor, and although reading of plans provides access to some 3-dimensional information, inferences are required in order to understand the building as a 3-dimensional entity. Examples of 2-dimensional information depicted in the plans which require inference-making to understand its 3-dimensionally are: 1) dotted lines indicate that there is an object hanging above in the ceiling of the level depicted; 2) thick pen weights indicate the location in the building through which the plan has been cut and hence an object which is outlined by a thick pen weight rises through that floor level; and 3) thin pen weights indicate that the object does not rise up completely to the ceiling of the depicted level. One of the main difficulties with regard to understanding this building in particular is that both the upper and roof levels are on 3 split levels, and the upper level has slots cut through the floor which correspond to sky lights in the roof allowing light to shine down from the roof to the lowest floor.

2. Relevant Literature

In addressing expertise in the comprehension of architectural graphics, this study draws upon literature from many sources, including cognitive science, psychology, and architecture. Although it is beyond the scope of this paper to present an extensive review of this literature (see Gobert, 1994 for a thorough review), some literature will be presented to provide readers with a suitable background for the research.

2.1. THE VIEW OF EXCEPTIONAL PERFORMANCE FROM AN UNDERLYING ABILITIES PERSPECTIVE

Throughout the history of psychological research, several different scientific approaches have been used to examine exceptional performance. The initial approach assumed that exceptionality was primarily based on general, inherited characteristics (e.g., Galton, 1869). However researchers since Galton began to evaluate the relationship between general ability and its relationship to superior performance and found only low correlations (Guilford, 1967), as have more recent studies (Cooper & Reagan, 1982; Hunt, 1980). For example, superior spatial ability was often assumed to be very important in chess (Chase & Simon, 1973); however, studies investigating the spatial (Doll & Mayr, 1987--cited in Ericsson & Smith, 1991), perceptual, as well as basic cognitive abilities of Grand Chess Masters (de Groot 1946/1978), elicited no significant findings. In general, the attempt to find superior cognitive abilities as explanatory mechanisms for exceptional performance has the complication that the specific characteristics that are purported to account for exceptional performance have become so integrated with that performance it is extremely difficult to rule out the possibility that such capabilities have been acquired as a result of the extensive experience in a domain (Ericsson & Smith, 1991; Chang, Lenzen, & Antes, 1985).

2.2. THE CONTRIBUTION OF SPATIAL ABILITY TO ARCHITECTURAL EXPERTISE

Although the relationship between architecture and spatial ability is intuitively compelling, research on this relationship also has been somewhat inconclusive. Data have been found both in support of and in refutation of the relationship between spatial skill and architectural performance. For example, architects are consistently more accurate than lay people at tasks involving spatial visualization; however, they also take longer than lay people to encode the stimulus materials on these tasks and it is uncertain whether this finding would be obtained if time for encoding was controlled for (Salthouse, 1991). Another intriguing finding about spatial visualization is that this skill declines rapidly in architects after retirement from the profession (Salthouse, Babcock, Skovronek, Mitchell, and Palmon, 1990). These findings collectively seem to suggest that spatial visualization is related to architectural skills; but this does not resolve the issue of whether enhanced spatial skills were present in architects before extensive training. Salthouse and his colleagues have proposed the distinction of "differential preservation" versus "preserved differentiation" to describe this issue (Salthouse, Babcock, Mitchell, Palmon, and, Skovronek, 1990; Salthouse, 1991). Respectively, these refer to whether experience in architecture leads to enhanced spatial abilities or whether the enhanced spatial abilities exhibited in architects always existed.

Both the inconclusive relationship between architecture and spatial skills, and the larger question of spatial skill as an explanatory construct (Lohman, 1988; Alderton, 1989) were taken into account in the treatment of spatial skills in the present research. Since it was beyond the scope of this research to investigate the relationship of spatial abilities to architectural performance, for the purposes of the present study it is assumed that spatial skills may be related (to some degree) to architectural tasks. With this in mind, subjects' scores on tests of spatial abilities were used as covariates only, thus, controlling statistically for potential differences in spatial skills amongst the subjects and permitting a clearer interpretation of the differences in the various dependent measures due to expertise.

2.3. THE VIEW OF EXCEPTIONAL PERFORMANCE FROM AN ACQUIRED SKILLS PERSPECTIVE

In brief, difficulties in establishing a connection between specific capabilities and exceptional performance, such as those cited above, have led to blind alleys (see Ericsson & Smith, 1991 for a thorough review). This has led researchers to investigate exceptional performance from an acquired skills perspective. This approach, called the "expertise approach" (Ericsson & Smith, 1991), is adopted in the present research, and attempts to account for exceptional performance in the domain of architecture in terms of the domain-specific knowledge and skills that one acquires through extensive experience in this domain. Briefly, the expertise approach has three major components (Ericsson & Smith, 1991): (1) the use of tasks which capture the essence of expertise on real-time performance in the domain, (2) the application of detailed analyses of superior performance in order to examine the cognitive phenomena associated with expertise, and (3) to account for the acquisition of processes and skills which mediate expert performance.

One of the objectives of the present research was to empirically investigate differences due to expertise on a task requiring the understanding of a building from its plans by investigating both the knowledge acquisition processes used in acquiring information from the plans, as well as the inferences made on this knowledge in order to understand the building as a 3-dimensional entity. It was hypothesized that these specialized knowledge acquisition and inference strategies are at least part of the specialized knowledge that experts in architecture possess.

3. Underlying Methodological Framework

The methodology employed in this research was developed for text comprehension (van Dijk & Kintsch, 1983; Frederiksen, 1988). These theories assume that comprehension is a stratified process in which semantic information from a text is represented by the learner in several levels. Briefly, this model encompasses three levels of representation, 1) syntactic parsing, 2) the encoding of semantic information, and 3) development of a situation model (van Dijk & Kintsch, 1983) or mental model (Johnson-Laird, 1983). The propositional level (the second level described) is regarded as an intermediate semantic level representing the conceptual meaning of the information presented. These propositions in turn provide a knowledge base from which a learner constructs a conceptual frame, i.e., a situation model (van Dijk & Kintsch, 1983; Kintsch, 1986) or a mental model (Johnson-Laird, 1983, 1985) of the higher-level information in the text or information source. These situation or mental models are higher-level semantic structures and are postulated to represent information in long-term memory.

It is important to note that by applying this framework to the comprehension of graphics, I am adopting the working hypothesis that <u>some</u> of the processes which are employed in the understanding of text should also operate in the understanding of graphic information sources, such as those processes used in semantic and conceptual understanding and encoding. By employing this model of comprehension, I am not denying the possible existence of levels of representation which are specific to the visual modality. The adoption of this framework for visual/graphical comprehension has been previously suggested (cf., Jackendoff, 1987). Furthermore, employing an existing theoretical framework is parsimonious since the common goal for cognitive science is to develop a single, unified theory which will be able to account for the processes involved in the comprehension and production of natural language, visual perception, memory, and reasoning (cf., Anderson, 1983; Newell, 1990).

3.1. TEXT COMPREHENSION VS. GRAPHIC COMPREHENSION AND ITS IMPLICATIONS FOR ARCHITECTURAL COMPREHENSION

The comprehension of textual information sources is very well documented (cf., Frederiksen, 1975, 1985; Kintsch, 1974, 1986, 1998; van Dijk & Kintsch, 1983; Britton & Graesser, 1996). By contrast, surprisingly little is known about how graphic information is understood. The first obvious difference between graphics and text is that graphics present all information simultaneously whereas text is presented linearly. The implications for the cognitive processing of the respective information sources is that, in the case of text which is structured sequentially, the cognitive processing follows the structure of the text (Larkin & Simon, 1987). Since all information in graphics is presented simultaneously (Thorndyke & Stasz, 1980), processing graphical information requires <u>additional</u> search processes to guide the acquisition of information (Larkin & Simon, 1987).

In the case of processing visual information sources, superior performance has been accounted for in terms of domain-specific schemata which provide search mechanisms in the form of perceptual and cognitive structures which influence the amount and manner in which information is processed and encoded in memory (Chang, Lenzen, & Antes, 1985; Gilhooly et al., 1988; Head, 1984). These encoding units and relationships between units are based on conceptual, semantic, and functional encodings which are meaningful within their respective domain (Chase & Chi, 1981; de Groot 1946/1978) and are developed in terms of requirements for the domain (Ericsson & Smith, 1991; Gobert, 1994). For example, in electronics, experts represent information by using functional units of circuit types (Egan & Schwartz, 1979). Similarly, in the case of topographic map reading, experts focused on highest and lowest points depicted (implicitly) in the map in order to understand the terrain (Chang et al., 1985). In the case of architecture, experts represent knowledge in chunks of spatial knowledge (Akin, 1979; 1986). Thus, the processes used for knowledge acquisition and representation in different visual domains will be different depending on the task demands of the particular domain, and in each case, skills which evolve through experience are especially adapted for performance in the respective domain (Ericsson & Smith, 1991).

It is hypothesized in the present research that experts in architecture possess skills and schemata permitting them to better search for, encode, and represent both 2-dimensional and 3-dimensional information from architectural plans. In additional to the literature on visual information sources, this hypothesis was based and motivated by earlier research in the domain of architecture (cf., Gobert, 1989;

Gobert & Frederiksen, 1988; 1989). Here, think aloud protocols (Ericsson & Simon, 1984) were collected from experts and sub-experts on a task requiring the comprehension of a set of architectural plans. It was found that there were 8 types of semantic information used to encode a building from its plans, namely: object identification, object description, object geometry, function, location, part structure, supporting structure, and circulation. These types of encodings are postulated to represent the second, i.e., the semantic or propositional level of representation from which mental models are constructed. Detailed analyses of think aloud protocols from this research (conducted for another purpose other than identifying search processes) led to noticing that experts' search processes were more systematic and integrative in terms of seeking out 3-dimensional information about the building compared to sub-experts. Sub-experts, on the other hand, used a haphazard, "floor by floor" knowledge acquisition strategy. It was hypothesized and directly investigated in the present study that these different knowledge acquisition processes used by experts and sub-experts lead to different conceptual representations, i.e., the knowledge acquisition processes used by experts lead to qualitatively better representations which were more isomorphic to the building itself as a 3-dimensional entity. Sub-experts' haphazard strategies, on the other hand, were likely to lead to representations which were more similar (at best) to the plans used to represent the building, rather than to the building itself.

4. Contributions To Research On Architecture

In addition to the potential contributions that the present research can make to both the study of comprehension and the study of expertise, the findings can provide valuable insight to the cognitive research on-going in the domain of architecture. Akin (1978) has summarized the cognitive research in architecture into the following four categories, each with its specific focus and goal. Briefly, these four areas are: (1) those which deal specifically with the design process and use empirical means to study this (Akin 1978, Baer, 1976; Eastman, 1970; Foz, 1973; Krauss & Myer, 1970); (2) those which utilize formal or algorithmic formulations for different data-storage or processing aspects of design (Freeman & Newell, 1971; Henrion, 1977, Herot, 1974; Newell, 1970); (3) research which approaches design as an example of problem-solving in an ill-defined domain (Eastman, 1969; Newell, 1970; Reitman, 1964; Simon, 1973); and (4) those which deal with the theoretical aspects of architectural design using the introspective knowledge of designers and empirical methods to model them (Goumain, 1973; Moran, 1970; Ramam, 1973; Simon, 1970; Weinszapfel, 1973). In addition to these, there have been studies conducted concerning expertise in architectural design (Akin, Dave, & Pithavadian, 1987; Foz, 1973).

The present research can be informative to research on architectural design problem-solving since the comprehension/representation process has been shown to be the first step in problem-solving in general (Simon, 1973) and in architecture (Akin, 1986). Architectural design is an excellent prototype of an ill-defined problem-solving task (Akin et al., 1987; Chan, 1990; Katz, 1993). The graphics which are produced during design problem-solving can be thought of as a trace of the design process. Akin (1986) claims that representation is the first necessary component in design tasks, in which knowledge is acquired about the design specification from texts, maps, sketches, photographs, and site plans. Foz (1973) in his study on the development of the architectural parti2[1] has pointed out the power of external

[1] 2 An ecoles des Beaux Arts term referring to the preliminary design, particularly as intended by the floor-plan organization.

representations during the course of designing. From the standpoint of the present research, graphics can be studied as communicative entities to be comprehended. Since this is an essential component of architectural performance, results from the present study can provide valuable information about the representational processes employed in various components of architectural performance.

5. Method

Purpose

To reiterate, the main objectives for this research were to characterize the nature of the comprehension processes involved in understanding of a building from its plans, and to investigate whether the knowledge acquisition processes employed in understanding plans as well as the resulting conceptual representations for the building differed due to expertise.

Subjects

A total of sixty-two people participated in this research. The expert sample was made up of 30 practicing architects, all with a minimum of ten years experience as practicing architects. The novice sample was made up of thirty students who had recently completed their second year of architecture at the University of Toronto. Testing students at an earlier point in their education was not possible since they may not have obtained a reasonable level of proficiency at reading the notational system used in architectural plans. Two additional architects, called "participant experts", also participated in this study. The protocols of these subjects were used for the purposes of developing interview materials for the purposes of the study such as the comprehension items used to assess subjects' understanding of the building.

Materials

The building.

The building which has been chosen as the input for this study is House II by Peter Eisenman (Eisenman, 1982). Of this building, three plans (lower, upper, roof) were provided.

Procedure.

Subjects were interviewed on an individual basis. The subjects, while viewing the plans, were asked to "Tell me in as much detail as possible all that they knew about the building from the plans in as much detail as possible." All think aloud protocols were recorded and transcribed verbatim.

After the subjects had studied the plans and gave a think aloud description, their understanding of the building were assessed using a comprehension test. This test assessed, primarily 2-dimensional comprehension, i.e., information which was directly depicted in the plans, and 3-dimensional comprehension, i.e., information about the building which required inference-making on the information given in the plans. Examples of 2-dimensional comprehension are: "Thinking back to the original plans, specify whether the following locations are either outside or inside: a) X12, b) X13, c) X14, d) X17" (subject is given the stripped lower plan in which different hierarchies of pen weights have <u>not</u> been used); "Describe the line of enclosure, i.e., separation between inside and outside of house, on the lower level, beginning on the N-W corner, moving clockwise" (subject is given the stripped lower plan). Examples of 3-dimensional comprehension are: "If you are standing in the location marked X7, facing west, what do you see and why?" (subject is given the stripped upper plan). "If you are standing in the location X21, how high from the floor is the ceiling above you?" (subject is given the stripped lower plan).

Next, the subjects were asked to draw two cross-sections of the building (these data were compiled with each subject's respective scores for 3-dimensional comprehension).

Lastly, four sub-tests of spatial ability were administered. These sub-tests were all taken from the *Kit of Factor-Referenced Cognitive Tests* (Ekstrom, French, Harman, & Dermen, 1976), and were chosen to assess three different factors of spatial ability, namely, Visual Memory, Visualization, and Spatial Orientation. Visual Memory is defined as "the ability to remember the configuration, location, and orientation of figural material". Spatial Visualization is defined as "the ability to manipulate or transform the image or spatial patterns into other arrangements". Spatial Orientation is defined as "the ability to perceive spatial patterns or to maintain orientation with respect to objects in space".

Coding of Think Aloud Data

Two types of protocol analysis were developed to investigate subjects' knowledge acquisition processes, namely, the proportion of systematic moves made, and the proportion of instances of articulated 3-dimensional search. Both represent a trace of the learner's search processes such that the object being described is purported to that being attended to (Ericsson & Simon, 1984; Gilhooly et al, 1988).

1) *Systematic Search***.** For this analysis, the clause (from the subjects' protocols) was used as the unit of analysis; the resulting score equals the proportion of systematic "moves" over the total number of moves in think aloud. Beginning with the first location mentioned in the subject's protocol, all subsequent "moves" were coded as either systematic (i.e., spatially adjacent in 2-dimensions) or haphazard (not spatially adjacent or not thematically related--coded separately). Examples of systematic search are:

"And so basically we are sort of entering the building, which is ... as described before, we are entering at the northeast end. As we enter we see the ... visually we see right through the open space which is the glass area as indicated in the ...so you are looking at the sheet of glass as you enter through here."

". . . so when you get to the top of the first set of stairs you come to this little entrance and bridge, that they call it, because of the openings. And there's a washroom, and you can actually look right through this corridor and see that there are two bedrooms."

Examples of haphazard search are: "And along the west, there are windows, this is the lower level plan. And there seems to be an overhead plane sticking out at the eastern upper part..."

2) *Three-dimensional Search*. Again, clauses of each subject's protocol were used as the unit of analysis; the resulting measure was proportion of instances of 3-dimensional search over total number of clauses generated per subject. Examples of 3-dimensional search are:

"The terrace has this particular pier that goes right through to the second floor". "There's a fireplace that is centered in the central column spacing that doesn't go up to the upper level plan."

"Well, I am referring to skylights which correspond with the openings in the upper level floor plan which allow light right down to the main floor."

". . . that wall doesn't go all the way up to the ceiling. So you can see over part of that."

Results for Learning Process Measures

1) *Effects Due to Expertise on 3-Dimensional Search.*

For the analysis contrasting the experts and the novices in terms of the instances of 3-dimensional search in the think aloud task, proportions were based on number of instances of 3-dimensional search to the total number of segments in the protocol. Although experts scored higher on this measure than did novices, this difference was not large enough to reach statistical significance [X_E=0.28, X_N=0.21; F=3.432, p<.070, n.sig.]. Table 1 summarizes the means and standard deviations.

TABLE 1. Cell means (and standard deviations) for measures by expertise

Measure	Experts	Novices
3-D search	0.28 (0.12)	0.21 (0.13)
systematic search	0.80 (0.12)	0.61 (0.20) *
2-D comprehension	22.94 (3.87)	19.27 (3.80) *
3-D comprehension	42.39 (7.61)	33.06 (8.51) *
building knowledge	3.08 (0.95)	2.78 (1.03) *
modern design know.	2.13 (1.32)	1.61 (0.87) *

* statistically significant at the .05 level of alpha.

2) *Effects Due to Expertise on Systematic Search*.
For the analysis contrasting the experts and the novices in terms of the number of systematic moves generated during the think aloud task, proportions were based on number of systematic moves to the total number of moves in the protocol. Experts made a significantly greater proportion of systematic moves than the novices [X_E=0.80, X_N=0.61; F=19.74, p.<.001]. (Novices made a significantly greater amount of haphazard moves than the experts [X_N=0.39, X_E=0.20; F=19.74, p.<.001]). Table 1 summarizes the means and standard deviations.

Results for Resulting Conceptual Representations

1) *Effects due to expertise in resulting representations of the building: 2-dimensional and 3-dimensional comprehension*.
For the analysis of differences due to expertise in the comprehension of information directly depicted in the plans, i.e., 2-dimensional comprehension and understanding of the building as it appears in 3-dimensions, i.e., 3-dimensional comprehension, the two variables were entered together in a multivariate analysis of variance.

An overall significant multivariate main effect was found favoring the experts (F_{Mult} =19.278, p<.001) for both 2-dimensional comprehension [F_{Univ}=21.265, p<.001] and 3-dimensional comprehension [F_{Univ} =37.178, p<.001]. Thus, the experts acquired more 2-dimensional information directly depicted the plans [X_E=22.94] than did the novices [X_N=19.27]. Furthermore, the experts were able to make more inferences on the information that they had acquired from the plans as reflected in their higher scores on 3-dimensional comprehension of the building [X_E=43.39; X_N=33.06]. Table 1 summarizes the means and standard deviations.

2) *Effects due to expertise in understanding architectural genre*
In order to investigate differences due to expertise in the understanding of the building's architectural genre, building knowledge (i.e., year of design & construction, etc.) and modern design knowledge (i.e., aspects of modern design) were used as measures. An overall significant multivariate main effect was found favoring the experts (F_{Mult} =5.696, p<.006) for both building knowledge [F_{Univ} =8.116, p<.006] and modern design knowledge [F_{Univ} =7.452, p<.009]. That is for both of these measures of architectural genre, the experts outperformed the novices [building knowledge: X_E=3.08, X_N=2.78; modern design knowledge: X_E=2.13, X_N=1.61]. Table 1 summarizes the means and standard deviations.

Results for Covariates

1) *Effects for Covariates on Learning Process Measures*

For the learning process measure of 3-dimensional search, one of the spatial abilities, namely, spatial visualization, was found to be a significant covariate [$F=6.825$, $p<.012$]. Spatial visualization is defined as "the ability to manipulate or transform the image or spatial patterns into other arrangements" (Ekstrom et al., 1976). Spatial orientation and Visual Memory were not found to be statistically significant covariates for 3-dimensional search.

For the number of systematic moves generated in the think aloud task, none of the spatial measures used as covariates were found to be significant; [visual memory: $F=2.003$, $p<.163$; spatial visualization: $F=.549$, $p<.462$; spatial orientation: $F=.377$, $p<.542$].

2) *Effects for Covariates on 2-Dimensional and 3-Dimensional Comprehension*.

Spatial visualization was a significant covariate for both 2-dimensional ($t=21.82$, $p<.034$) and 3-dimensional comprehension ($t=2.666$, $p<.011$). The other two covariates which were included, namely, Visual Memory and Spatial Orientation did not reach statistical significance.

3) *Effects for covariates on architectural genre*.

For the comprehension of information regarding the building's architectural genre, i.e., building knowledge, two of the three covariates were statistically significant. Specifically, Spatial Visualization ($t=1.966$, $p<.055$) and Spatial Orientation ($t=2.871$, $p<.006$) were significant.

Discussion

1) *On The Nature Of Expertise In Understanding A Building From Its Plans*.
2)

Both systematic and 3-dimensional search were designed to address the degree to which subjects "moved" systematically through the plans in acquiring knowledge about the building. These measures take into account the order in which information was acquired by the subjects as reflected in their think aloud protocols and as such are assumed to present a trace of the learner's search processes in that the object being described is that which is currently being attended to (Ericsson & Simon, 1984; Gilhooly et al., 1988).

In summary, the processes for acquiring information from plans, particularly those for systematic search, provide support for the notion that experts in this domain selectively attend to information depicted in architectural plans differently than novices. It is hypothesized that these knowledge acquisition processes are directed by specialized schemata developed through extensive experience with architectural plans. Systematic search processes, hypothesized to be guided by prior knowledge schemata, have been shown to lead to richer conceptual representations in electronics (Egan & Schwartz, 1979) and map-reading (Thorndyke & Stasz, 1980). In architecture, it is likely that the advantage observed for experts on 2-dimensional comprehension of the plans is due, at least in part, to the systematic search processes which were guided by prior knowledge schemata, developed through extensive experience with architectural plans.

The relationship between the search processes employed to acquire 3-dimensional information across the plans and the resulting representation for 3-dimensional understanding of the building is somewhat less direct however. That is, although it was clearly demonstrated that experts' 3-dimensional understanding of the building was superior to that of novices, experts' search processes employed to acquire such 3-dimensional information from the plans were not (significantly) superior to those employed by the novices. It is possible that all information which was encoded from the plans regarding its 3-dimensional nature was not articulated in the experts' think aloud protocols. Experts' knowledge and strategies can become routinized such that not all the contents of working memory are articulated in think aloud protocols (Johnston & Afflerbach, 1985). However, another interpretation of this finding is favored; that is, once information has been acquired from the 2-dimensional plans, representing the building as a 3-dimensional entity requires inference-making that operate on the graphical symbols (Hunt, 1978). As previously discussed, 2-dimensional comprehension is assumed in the present research to be an intermediate level of representation (similar to the propositional or textbase level of representation in models of text comprehension (Kintsch, 1986)) from which higher-level representations, i.e., in this case, 3-dimensional understanding is constructed. The present data suggest that experts had a better understanding of the 2-dimensional information depicted in the plans, as well as a better understanding of the building as a 3-dimensional entity than novices. The advantage obtained for experts on 3-dimensional understanding of the building is hypothesized to be only partly due to the acquisition of more information directly depicted in the plans (i.e., their 2-dimensional comprehension). That is, in addition experts are hypothesized to have advantages over novices in terms of their ability to make inferences on the 2-dimensional information depicted in the plans in order to understand the building as a 3-dimensional entity.

Ericsson and Smith (1991) suggested that skills and processes in particular domains evolve so as to make execution of domain-related tasks more efficient. In the case of architecture, it is likely that experts develop knowledge acquisition processes, such as systematic and 3-dimensional search, to enable them to more efficiently and quickly about buildings from their plans. Additionally, these data suggest that experts have developed specialized skills for making inferences about the 3-dimensional nature of the building from its plans which are 2-dimensional.

2) *Regarding Spatial Ability.*

Although it was beyond the scope of this thesis to carry out an in-depth examination of the contribution of various spatial abilities to architectural tasks, previous research has shown that spatial visualization in particular is important in the profession of architecture (Salthouse et al., 1990). For this reason, three factors of spatial ability were used as covariates in the present study.

The findings of this research suggest that spatial visualization may be related to the acquisition of information from architectural plans (i.e., 3-dimensional search), to the comprehension of information directly depicted in the plans (i.e., 2-dimensional comprehension), and to the development of higher-level representations embodying the 3-dimensional characteristics of the building (3-dimensional comprehension). Additionally, spatial visualization and spatial orientation may be related to the abstraction of high level conceptual knowledge about the building. These results are potentially helpful for subsequent studies which specifically seek to investigate the contribution of various spatial abilities to performance on architectural comprehension as well as other architectural tasks, e.g., architectural design.

In accordance with Chase and Chi (1981), who studied the recall of architectural plans by experts and non-experts in architecture, it is argued here that it is likely that there are many components of spatial knowledge, that spatial skills can come about through a variety of different experiences, and that a full understanding of the contribution of spatial ability to domain specific performance in architecture requires more research. In order to address these relationships more thoroughly, research must focus on the precise relationship between low level processes required to perform psychometric tests of spatial ability such as visualization and high level processes required for domain-specific tasks, such as understanding a building from its plans. These include knowledge acquisition processes for directing search, encoding processes for knowledge directly depicted in the plans, understanding conceptual knowledge communicated in the plans, as well as representational and inferential processes required for developing 3-dimensional representations of a building.

3) *On The Use Of The Text Comprehension Model For Investigating The Comprehension Of Graphics.*

The results obtained in this study extend research on text comprehension to comprehension of graphic sources of information. They suggest certain parallels between comprehension of these information sources. While there are undoubtedly representations having characteristics of a spatial and/or visual nature involved in the comprehension of graphic information, this study was not designed to investigate the spatial or visual representation of architectural plans. Although many questions remain, the theoretical and methodological approach adopted appear to provide a suitable means for investigating the comprehension process for graphic information sources. This in turn can contribute to a more general model of the comprehension process, and to characterizing one aspect of expertise in architecture.

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