Understanding Phenomena: Investigating Structure-Function Relationships

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Abstract

As Simon (1981) has pointed out, coming to characterize phenomena as functional systems is fundamental for our understanding of the natural and man-made worlds. Yet little is known about people's propensities for making such characterizations. In contrast to previous research that has focused on unfamiliar, opaque systems, the study reported here investigated experts and novices relative use of structure-function relationships to understand a familiar, inspectable system--a bicycle. As the study shows, the experts, but not the novices, spontaneously and consistently utilized a systems approach to characterize this familiar object.

Introduction

One of the most salient features of human life is the continual need to effectively understand and deal with a wide-range of phenomena, for example, diagnosing automobiles that will not start, writing complex computer programs, forecasting the weather or predicting predator-prey cycles. Like many natural and man-made phenomena, these four cases can be described as *systems* in which functions are produced by structured collections of components.

Central to the system concept is the idea of functional decomposition in which a phenomenon is considered in terms of its function(s) and underlying structure(s) (Bradshaw, 1992; Goel & Pirolli, 1992; Simon, 1981). For example, Bradshaw has argued that the Wright brothers' success in designing the first powered airplane was due to their decision to characterize flight as a set of independent subsystems. They then designed a collection of systems, each of which accomplished one of the functions necessary for powered flight.

Coming to decompose phenomena in terms of function and structure is an important means of developing our understanding of the man-made and natural worlds (Simon, 1981). As Miyake (1986) has pointed out, understanding a function requires focusing on the underlying mechanism. That is, understanding develops as individuals come to characterize phenomena in terms of structure-function relationships and not simply as collections of components. Moreover, a focus on functional decomposition appears to be an important aspect in the development of expertise (Lesgold & Lajoie, 1991). The study reported below investigates the relative ability of experts and novices to construe a familiar system--a bicycle--in terms of structure-function relationships.

Systems Research

Despite the apparent usefulness of a systems approach for understanding the natural and man-made worlds, there has been relatively little research into people's ability to use such knowledge. Previous systems research has looked primarily at people's ability to list the structures making up common systems, for example, elementary and high school students' knowledge about the constituent parts of the circulatory and digestive systems (e.g., Arnaudin & Mintzes, 1985, 1986; Catherall, 1981; Gellert, 1962). This work found that older children list more of the components than do younger children; however, it has provided little insight into people's understanding of how structures and functions are related. By focusing only on the constituents of structures rather than structure-function relationships, this work implies that systems are simply collections of parts.

Previous work has also complicated systems research by choosing complex, opaque systems, such as the circulatory system, that are closed to direct inspection. A more appropriate beginning point would be to investigate how people deal with familiar, relatively simple, inspectable systems. That is, people are more likely to first think of structure-function interactions with systems that they frequently see in operation and open to inspection. One familiar, inspectable system is the bicycle.

In contrast to many systems, such as the circulatory or digestive systems, a bicycle can be visually decomposed into a small set of relatively simple, visible, and largely independent subsystems: the drive, braking, steering and shifting subsystems. Complete understanding of the operation of a bicycle requires grasping the interactions among these four functions. Yet, the relative independence of the functions suggests that much of a bicycle's behavior can be understood by focusing on each subsystem in isolation.

Although most people are familiar with bicycles, very few spend extensive periods of time riding or maintaining them. However, there is one group that does have considerable riding and maintenance experience--competitive cyclists. Contrasting experts'--bicycle racers--and novices' characterization of the bicycle's subsystems may provide insight into people's ability to construe a system--the bicycle--in terms of structure-function relationships. This study specifically addresses two questions:

1. What happens when experts and novices are asked to group a selection of bicycle components? Knowledge of systems suggests the ability to decompose the system into functional arrangements, not simply on the basis of physical proximity or similarity of components. If

expertise is associated with a focus on structure-function relations, then only the experts should use function to group components.

2. What happens when novices are asked specifically to select from a group of components those necessary for a specific functional system, such as the drive system? It may be the case that novices are able to construe a familiar object in terms of functional systems when specifically asked to do so. This would suggest that, at least with familiar phenomena, even novices have some implicit understanding of how structure and function are related.

Method

Participants

Eighteen adult novices and 9 adult experts, all students at a large midwestern university, participated in this study. Experts were volunteers from a bicycling club in the same community. All participants had been bicycling since childhood and were familiar with bicycles. The criteria for determining whether a participant was an expert or a novice was based on the degree of bicycle maintenance a person performed. Experts performed all of their own bicycle maintenance; beyond occasionally inflating the tires, novices performed none of their own bicycle maintenance.

Procedure

A modified card-sort task was used to explore people's spontaneous grouping of bicycle components (a bicycle with labeled components was available for reference throughout the study). Participants were shown a set of index cards in random order, labeled with the following bicycle components: frame, fork, front and rear wheels, front and rear derailleurs, front and rear gears, chain, pedals, cranks, shift levers, brakes, brake levers, handlebar, saddle, horn, and pump. Participants were asked to put the cards into groups of components that "go together" and to justify their groupings. They were free to make as many groups as they wished.

Following this general probe, I investigated people's ability to adopt a systems perspective while thinking specifically about each of the bicycle's functional subsystems. Participants were asked to select and justify the components they thought important for each subsystem. Participants were asked to think aloud throughout the study, and protocols were audiotaped for later analysis.

Interview Coding

To characterize participants' justifications for both the spontaneous and subsystem sorting questions, a coding scheme was developed by reading and categorizing three protocols from each of the groups. These categories reflect the many ways in which participants justified their component groupings. This scoring scheme was subsequently applied to the remaining protocols. A second individual then applied the scoring scheme to half of the protocols from each group. For the spontaneous sorting question, the percentage of initial agreement was 88%; for the subsystem sorting questions, agreement was 95%. Disagreements were resolved through discussion.

Table 1 shows the classification scheme. Justifications can be broken into two general categories: *systemic* and *non-systemic*. Only systemic justifications referred specifically to structure-function relations. Non-systemic justifications were broken down into six sub-categories: justifications focusing on the components a cyclist is in physical contact with while riding were classified as *agent-based*; justifications referring to the components that define a bicycle were classified as *primary*; groupings of unnecessary components were classified as *tertiary*

Table 1: Participants' justifications for component groupings.

Category	Definition	Example
Systemic	Explicit mapping of function to structure	"Levers, brakes and wheels work together to stop the bike."
Agent-Based	Components the cyclist is in contact with	"Levers, shifters, and pedals, because those are the things you touch on a bike."
Primary	Definitive components	"Wheels, frame and fork--without those you don't have a bike."
Tertiary	Unnecessary components	"You don't need the pump."
Contiguous	Groups based on contiguous components	"Front wheel is connected to the fork, and that is connected to the handlebar."
Nominal	Components with common name	"Front and rear wheels, because they are both wheels."
Miscellaneous		"The chain, gears and wheels, they all go around, so I'll put them together."

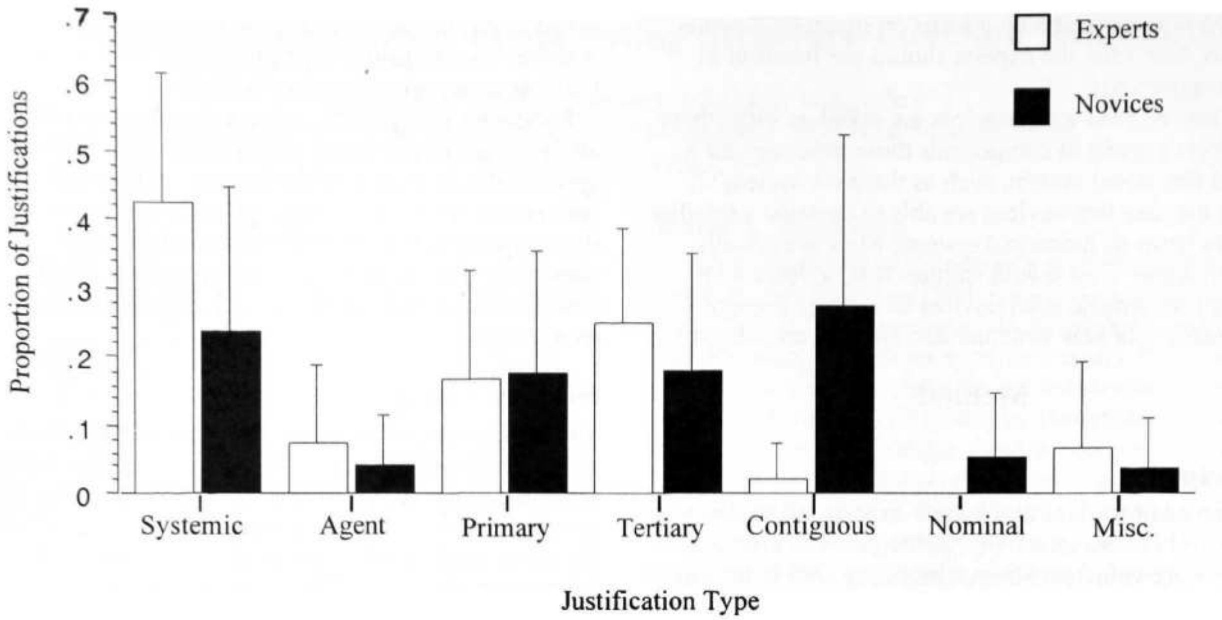

Figure 1: Mean proportion of justifications by group.

justifications; justifications highlighting groupings based on component proximity were classified as *contiguous*; and *nominal* justifications referred to groupings based on components that shared a common name. Justifications that did not fall into any of the above categories were classified as *miscellaneous*. Given the low proportion of miscellaneous justifications across groups, this category was excluded from the analyses reported below.

Results

Spontaneous Sorting Question

The initial sorting question provided evidence of how people spontaneously conceptualize a bicycle. As discussed above, a bicycle can be decomposed into four functional units. Thus, a structure-function approach should lead participants to group the component cards into four functional groups plus an "accessories" group (e.g., pump, horn, and seat). The results show that experts and novices produced approximately four groups each on average.

At first blush, the above result suggests that experts and novices alike might be approaching the task from a systems perspective. However, as Figure 1 shows, participants used a variety of justifications to support their spontaneous groupings. Paired t-tests were conducted comparing the groups on each of the six justification categories described above. The tests revealed that experts made systemic references significantly more often than did the novices, $t(25) = 2.24$, $p < .05$. Moreover, experts made significantly fewer justifications based on contiguous components than did the novices, $t(25) = 2.96$, $p < .01$. Finally, although none of the experts ever made a nominal justification, 5% of the novices' justifications were of this form.

This analysis of participants' justifications suggests that only the experts relied on structure-function relationships when spontaneously grouping components. However, all participants used a mixture of approaches for justifying their groupings. In order to characterize a participant's overall approach to the spontaneous grouping task, they were categorized according to their modal justification type. Comparing the groups on their preference for systemic versus non-systemic (i.e., agent-based, primary, secondary, contiguous, or nominal) justifications revealed that more experts (89%) than novices (50%) preferred making systemic justifications, χ^2 (1, $N = 27$) = 3.89, $p < .05$.

Subsystem Sorting Questions

Responses to the general sorting task suggest that only the experts consistently used a system stance for spontaneously sorting the bicycle components into groups. However, it could be that novices can consider the functional nature of systems when explicitly asked to do so. To explore this possibility, participants were asked to specify which components were important for each subsystem function.

Adopting a systems focus requires that one isolate, at least temporarily, the system of interest from the surrounding structures. I refer to this isolation ability as the *independence* competency. Further, participants' ability to select all of the components in a system reflects their understanding of which components are required for the function under consideration. For example, a sufficient drive subsystem requires at a minimum the front and rear gears, the chain, the cranks and the rear wheel. I refer to the ability to select all the required components for a system as the *sufficiency* competency. In addition, participants' choices and justification of the most important component in each subsystem can reflect their stance towards the task. Thus participants were asked to justify their choice of the most important component in subsystem. Justifications were coded using the scheme described above.

Independence Competency Across subsystems, between 78% and 100% of the experts and novices were able to consider each of the subsystems in isolation when asked to do so.

Sufficiency Competency In order to assess subsystem sufficiency, five additional experienced cyclists were asked to collaboratively determine the minimum number of components necessary for each of the four functions. Sufficiency was judged by matching participants' subsystems against this template.

For each subsystem, a Chi-square analysis compared the groups on the number of participants meeting the sufficiency criterion. These analyses revealed that between 89-100% of the experts and 72-77% of the novices were able to generate sufficient steering, shifting, and braking subsystems; differences were non-significant. However, although 100% of the experts were able to construct a sufficient drive system, only 33% of the novices were able to do so, χ^2 (1, $\underline{N}$ = 27) = 10.8, $\underline{p}$ < .01. Inspecting the protocols revealed that the novices most often failed to include the front and/or rear gears in their drive subsystems.

Together, performance on the independence and sufficiency competencies show that the groups, in general, had little difficulty isolating functions. The drive system represents an interesting exception in the case of the novices.

Component Justification Participants' justifications for their choices of the most important components provide additional insight into their utilization of system knowledge. For example, an agent-based justification suggests that a participant is focusing on *where* control over the subsystem is established; in contrast, a systemic justification suggests that a participant is concerned with *how* the function is achieved.

For each subsystem, I compared the proportion of participants in each group who made systemic references while justifying their component selections. As Table 2 shows, more experts than novices produced systemic justifications when discussing the steering subsystem, χ^2(1, $\underline{N}$ = 27) = 11.20, $\underline{p}$ < .0001; the shifting subsystem, χ^2 (1, $\underline{N}$ = 27) = 6.70, $\underline{p}$ < .01, and the drive subsystem, χ^2 (1, $\underline{N}$ = 27) = 15.01, $\underline{p}$ < .001.

Thus, in general, only the experts justified their component selections on the basis of structure-function relations. However, there was one exception to this general pattern; almost half of the novices made systemic justifications when discussing the braking subsystem. Unlike the other subsystems, the functional relationships within the braking subsystem are visible, relatively simple and linear: squeezing the brake levers actuates the brake calipers, which in turn squeeze the rim of the wheel. Moreover, for many people, understanding how to stop

Table 2: Proportion of participants providing systemic justification for each subsystem

	Subsystem			
	Steering	Shifting	Drive	Braking
Experts	.67	.67	.78	.78
Novices	0	.17	.05	.44

a bicycle is a matter of considerable importance; in extreme cases it could be a matter of life or death. This suggests that a systems focus might first arise when people deal with very simple, but personally important, systems in which they can easily observe and experience structure-function relationships.

Justification Preference Extending the above analysis, the consistency of participants' justification for their choice of the most important components was explored. Participants were considered to have a justification preference if they offered three or more justifications of a single type (e.g., systemic, agent-based, primary, etc.), otherwise they were classified as having no justification preference. Across subsystems, 67% of the experts consistently justified their component choices on the basis of structure and function; however, none of the novices did so. In fact 55% of the novices showed no preference for any particular form of justification.

The Bicycle-Cyclist System

Although participants were not specifically asked about the role of the cyclist, a number of them spontaneously commented on the dynamic nature of the cyclist-bicycle interaction. A rider can be considered from two different, albeit related, perspectives: (a) as a source of power and control imposed on the bicycle and (b) as a dynamic, integral, part of a cyclist-bicycle system. In the former perspective, a cyclist is regarded simply as a source of energy for pedaling and as an actuator of the shifting, steering and braking subsystems. The latter perspective subsumes the former, but in addition, regards a cyclist as a component in the steering, braking and drive subsystems. For example, by shifting body position while cornering, a rider can change the radius of the turn. By moving back on the saddle during braking, a cyclist weights the rear wheel, which increases traction and subsequently improves braking. Shifting forward on the saddle while riding up a hill allows a rider to increase his/her pedal cadence; moving back on the saddle leads to a decrease in pedal cadence but increases the effective length of the leg-foot lever, allowing the application of greater torque to the pedals.

All participants have probably experienced the effects of shifting body position while bicycling--people intuitively re-position their bodies to balance and steer their bicycles. However, inspection of the protocols showed that although seven of the nine (78%) experts made at least one comment about the integral role of a cyclist while riding a bicycle, only two of 18 (11%) novices did so. Thus, although all of the participants could ride a bicycle, only the experts had developed an explicit understanding of the nature of the dynamic interaction between cyclist and bicycle.

Discussion

The current study was motivated by an interest in seeing how novices and experts think about a familiar, inspectable system--a bicycle. As the results show, only the experts spontaneously construed a bicycle as an assembly of semi-independent functional subsystems. In contrast, the novices justified their spontaneous component groupings with references to such principles as agency, component contiguity, component names, and occasionally function. Novices appear to typically analyze even familiar systems by focusing on surface characteristics, such as component contiguity, rather than structure-function relationships. Experts, on the other hand, immediately focus on structure-function relations when analyzing a familiar system.

Of course, it is not the case that other perspectives, such as focusing on the relative location of different components, cannot be useful. Tversky and Hemenway (1984) stressed that in many cases, parts are organized in unique *configurations* according to function. Moreover, they claim that decomposition of part configurations forms the basis for naive induction--part structures are used to comprehend, infer, and predict function. However, as other work has shown, overreliance on location as a heuristic for determining function can be misleading (Egan & Schwartz, 1974; Lesgold & Lajoie, 1991). For example, Lesgold and Lajoie argued that skilled electronics troubleshooters use their domain knowledge to guide their problem solving, knowing that in many cases the function of interest is governed by non-contiguous components.

As the above results show, in general, the experts and the novices had little difficulty focusing on individual subsystems in response to the specific subsystem probes. The drive subsystem represents an interesting exception for the novices. One possible explanation is that subsystems that are visible during operation or directly experienced, and personally important are more accessible to novices than subsystems that are not.

Thus, experts and novices did not differ greatly in their ability to construct appropriate subsystems, However, their justifications of the most important subsystem components do reflect differences in how the groups characterize systems. Experts appear to consistently focus on how the function under investigation is produced; in contrast, few novices showed any consistency in the type of justification offered. This suggests that although novices have some conception of the components that make up some of the bicycle's subsystems, they have little understanding of the functional relationships between components; that is, how a collection of components produce a given function.

Adopting a focus on structure-function relationships--a systems perspective--is potentially a powerful means for understanding the link between structure and function. Yet, as this study shows, simply using a familiar, inspectable system is insufficient for non-experts to spontaneously adopt a system stance. Lesgold and Lajoie (1991) proposed three characteristics of expert troubleshooting that may underlie the successful adoption of a system stance: (a) knowledge of how constituent components work, (b) functional understanding of components, and (c) understanding of relations between components and the larger system. That is, increasing differentiation and increasing integration are characteristic of an expert's knowledge about systems.

However, the question that now emerges, is how do people come to characterize systems in terms of structure-function relationships? Miyake (1986) argued that *understanding* phenomena develops through an iterative search in which identifying a function subsequently promotes a search for the underlying mechanism. More specifically, a number of researchers have suggested that coming to understand any system begins with constructing an appropriate mental model (Bobrow, 1985; de Kleer & Brown, 1983; Keiras & Bovair, 1984; Moray, 1987). These models are cognitive structures that embody specific structure-function relations and can be used to make predictions about system behavior. However, as Norman (1983) pointed out, the majority of people's day-to-day mental models may incorporate only partial descriptions of structure and function. Consequently, in many cases mental models are not sufficiently detailed to be testable. This suggests that the role of mental models in the development of structure-function mappings needs to be investigated.

In summary, coming to understand phenomena appears to require understanding the underlying structure-function relations. As this study showed, experts, but not novices, spontaneously and consistently characterize a familiar system in such terms. However, what is less clear is the process by which people come to construe phenomena in terms of systems. Specifically, what is the process by which novices come to develop structure-function mappings? Further, what role does such knowledge play in the development of expertise? Future work needs to address these issues.

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