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Use of Structure Mapping Theory for Complex Systems

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Abstract

It is widely agreed that similarity is an important factor in transfer of training. However, the precise role of similarity in transfer is not well understood. We believe that the account can be clarified by a finer grained analysis of similarity. In this research we consider two factors that should affect transfer between two systems: (1) surface similarity, which we operationalize as similarity between individual device components; and (2) shared systematicity whether the learner possesses a coherent mental model of the original device that can apply to the second device.

Subjects learned an operating procedure for a simulated device and then were asked to transfer that procedure to a new device. Two factors were varied: (1) the systematicity of the original device model - whether the subjects were given a systematic causal model or simply a set of operating procedures; and 92) the degree of surface similarity between corresponding device components (called transparency). The dependent measure was the number of trials to criterion in the original and transfer devices, and in the same target device with an additional load task.

The results show effects of both variables. Having a systematic mental model greatly facilitated learning of the initial device, and may have also promoted transfer to the target device. Transparency had strong effects on transfer: subjects learned the new device fastest when the corresponding components were highly similar, and slowest when there were spurious similarities between target components and noncorresponding base components (the cross-mapped condition). These results suggest that there are at least two separable factors that promote transfer: (1) the systematicity of the domain model; and (2) surface similarity of corresponding components.

In this research we examine the determinants of transfer of training of a device model. It is widely accepted that similarity is a key determinant of transfer of training. But the precise role of similarity in transfer is not well understood. Novick (1985) points out that different studies have led to different conclusions. Some studies indicate that similarity promotes positive transfer; some that similarity often fails to create transfer (e.g., Reed (1985), Gentner & Landers (1985), Gick and Holyoak, (1983)); and some that it leads to negative transfer. We believe these contradictory findings can be resolved by a more fine-grained account of similarity. In particular, we propose to analyze the transfer situation from the viewpoint of analogical mapping.

Structure-mapping

Gentner's (1980, 1983, in press) structure-mapping theory of analogy provides a framework for our analysis of transfer of training. It describes the rules by which people interpret an analogy. In structure-mapping, analogy is defined as a mapping knowledge from a familiar domain (the base) into another, usually less familiar, domain (the target). In structure-mapping the following rules apply.[1] Objects in the base are placed in one-to-one correspondence with objects in the target:

$$M: b_i \rightarrow t_i$$

Predicates are mapped from the base to the target according to the following mapping rules:

(1) Attributes of objects are dropped:

e.g., [RED (b_i)] → [RED (t_i)].

(2) Certain relations between objects in the base are mapped across:

e.g., COLLIDE (b_i, b_j) → COLLIDE (t_i, t_j)

(3) The particular relations mapped are determined by the systematicity principle, which states that a base predicate that belongs to a mappable system of mutually constraining interconnected relations is more likely to be imported to the target domain than is an isolated predicate. For example,

$$\text{CAUSE [PUSH } (b_i, b_j), \text{ COLLIDE } (b_j, b_k)] \rightarrow$$

$$\text{CAUSE [PUSH } (t_i, t_j), \text{ COLLIDE } (t_j, t_k)]$$

Thus in true analogy the object correspondences are determined not by any intrinsic similarity in the objects themselves, but by their roles in the matching relational structures.[2] The point of an analogical mapping is to maximize overlap in relational structure.

[1] We give a brief summary of structure-mapping theory here. A fuller description of the theory is given in Gentner (1983). For a computer-simulated process model, see Falkenhainer, Forbus and Gentner (1986).

[2] This distinguishes analogy from literal similarity in which intrinsic object similarity is important.

Figure 1 shows an example of analogy: the Rutherford analogy between the solar system and th hydrogen atom.

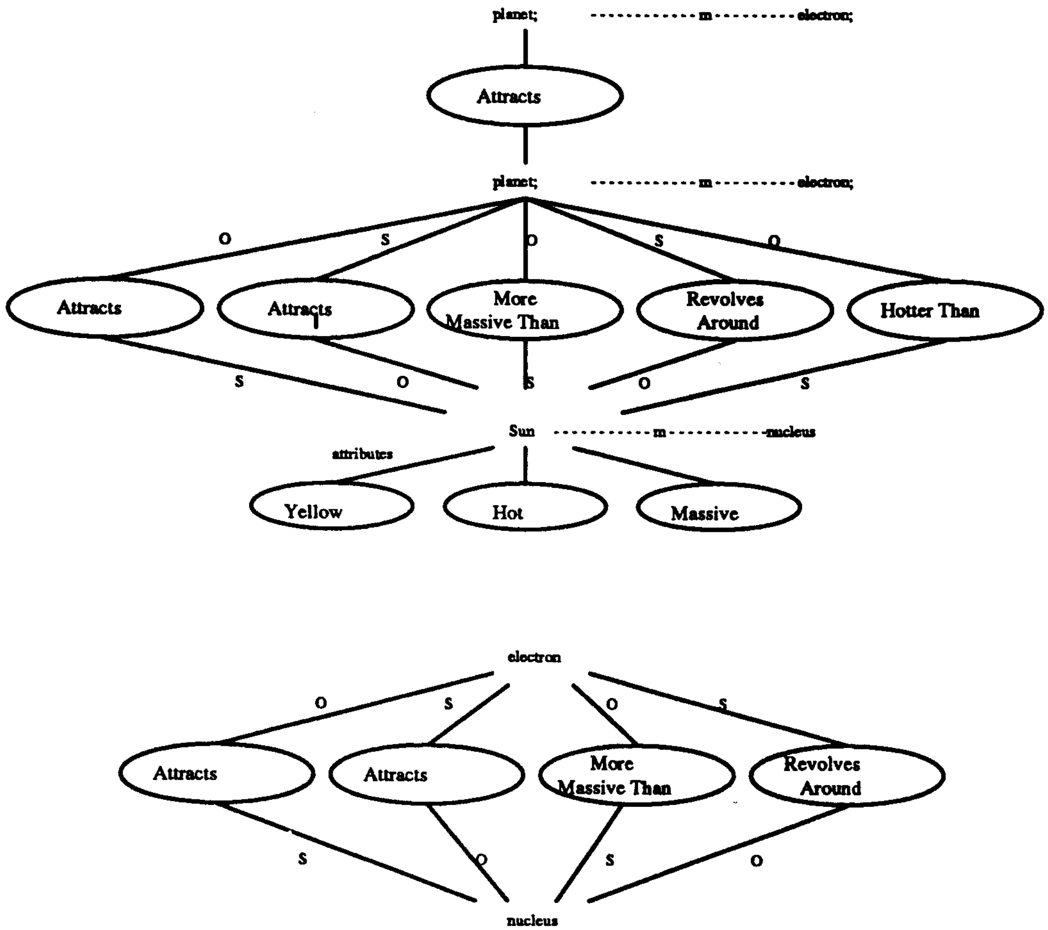


Figure 1: Structure mapping for the Rutherford analogy: "The atom is like the solar system."

To understand this analogy, a person must find the one-to-one correspondence between the objects of the solar system and the objects of the atom that gives a maximally systematic predicate match. Here, the most systematic set of matching predicates is CAUSE [MORE-MASSIVE-THAN (sun, planet), REVOLVE-AROUND (planet, sun)]. Thus the best object correspondences are sun 4 nucleus and planet 4 electron. Base relations belonging to the system, such as MORE-MASSIVE-THAN (sun, planet), are preserved; isolated relations, such as HOTTER-THAN (sun, planet) are discarded; and object attributes, like YELLOW (sun) and MASSIVE (sun) are dropped.

This kind of systematic match allows new predictions: predicates belonging to the base system but not present in the target can be mapped across as candidate inferences. Based on this discussion, at least two separate factors should contribute to the ease of analogical transfer: the systematicity of the base model, and the transparency of the correct object correspondences.

Systematicity in Transfer

A good analogy conveys a coherent system of connected knowledge, not simply an assortment of independent facts. The systematicity principle reflects this preference for coherence and deductive power in analogy. [3] Empirical studies have shown that adults focus on systematic relational structure in interpreting and evaluating analogy (Gentner, 1980; Gentner r& Landers, 1985; Gentner, in press; for a more general treatment of mental models see Gentner & Stevens, 1983). There is also evidence that systematicity may play an active role in guiding the on-line mapping process (Gentner & Toupin, 1986). The presence of higher-order relations may help constrain and guide the mapping of the lower-order relations. For example, if an error is made in mapping a target, then it is more likely to be detected and corrected if there are higher-order relations that constrain it.

Based on this line of reasoning, we believe that the presence of a systematic model of the base domain should increase the transfer accuracy between analogous devices.

Transparency in Transfer

Another factor that should be important in the mapping process is the transparency of the object correspondences. Transparency is defined as the degree of intrinsic similarity between corresponding component objects: Transparency is high when the surface similarity is strong between pairs of corresponding objects in the base and target domains. As we have discussed, transparency is irrelevant to determining the object correspondences in an ideal analogizer. But in actual practice, the ease of determining object correspondences may influence people's performance in achieving a correct analogical match. To take an extremely simplified example, it may be easier to solve 2:4:20: (40) than to solve 2:4::10 (20). Even though both examples are equally valid analogies, it may be easier to match 4 -> 40 than to match 4 -> 20. To the degree than one can easily determine how the objects in the base correspond with the objects in the target, the transfer of the predicate structure from base to target should be easier. Thus, we believe that transparency will have a strong effect on transfer accuracy.

The experiment reported here used a computer-simulated device. The device panel consisted of a set of interrelated gauges indicating system parameters such as the speed and engine temperature of a ship. Subjects learned how to operate the device, and then transferred their operational procedures to a second device. In each case, we measured the number of trials they needed to reach a set criterion. In order to test whether having a coherent causal model of the original device would improve subject's ability to transfer training to another device, we gave subjects either a systematic or a non-systematic model of how to operate the original device. We predicted that the systematic model would enable subjects to better perform the transfer. We also predicted that having a systematic mode would speed the initial learning, based on Kieras and Bovair's (1984) findings.

[3]Note that the systematicity principle requires that the relational chain be mappable from the base to the target. Thus, a relational chain, such as a causal chain, in the base that matches a relational chain in the target constitutes good support for the existence of its members.

Our second question was whether transfer accuracy would be affected by the transparency of the object correspondences between the base and target. We used three levels of transparency: (1) high transparency - the target components looked very similar to corresponding base components (e.g., the speed gauge in the target resembled the speed gauge in the base); (2) medium transparency - target components looked quite different from corresponding base components; and (3) low transparency (cross-mapped condition) - target components looked similar to non-corresponding base objects (e.g., the speed gauge in the target resembled the temperature gauge in the base). In cross-mapping the object similarities are in conflict with the functional similarities between the base and target domains. A given target object looks like one of the base objects, but its role in the relational structure is different. We predicted that cross-mapping would greatly disrupt transfer.

A third question was whether the effects of systematicity and transparency in transfer would increase when the workload demands increased. Subjects were given an additional task (called the load task) to perform while operating the target device. As in the other tasks, the measure of performance was number of trials to criterion.

Method

Subjects. Subjects were 54 undergraduates at the University of Illinois with little or no background in physics, who were paid for their participation.

Devices. Subjects learned to operate a computer simulated device panel like that shown in Figure 2a. For ease of presentation, we will describe the systematic condition and point out the differences with the non-systematic condition when necessary. Each panel consisted of six gauges representing the following parameters: engine thrust, speed of the ship, the level of coolant in the engine, the coolant gauge which controlled coolant level, engine temperature and distance traveled. These parameters were linked by a causal model, shown in Figure 3. In the systematic condition, subjects were given a scenario about a steamship that instantiated this causal model (See Kieras and Bovair, 1984). Subjects had direct control of two parameters: (1) the engine thrust gauge, which was positively related to the speed; and (2) the opening of the coolant gauge, which was positively related to coolant level. They controlled these parameters by pressing keys on the computer keyboard. Coolant level and engine speed worked opposite one another to influence the temperature, while coolant level held temperature down. The subjects' task was to complete a specified distance in the given amount of time. This was operationalized as lighting all four lights in the distance gauge before running out of time. In the non-systematic condition, subjects were given the same set of operating procedures, but no systematic causal model to organize their knowledge.

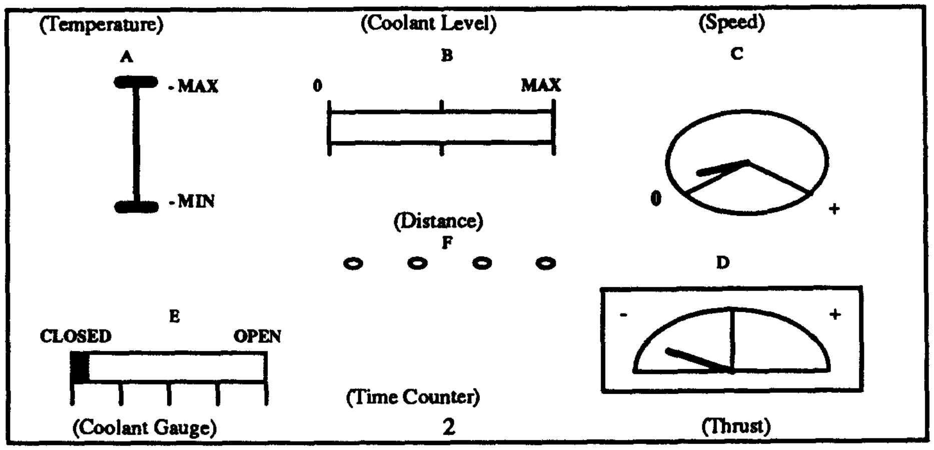
Transparency conditions. There were three mapping conditions which corresponded to high, medium and low transparency:

S/S: Similar gauges / Similar functions (High Transparency)

D: Different gauges / Similar functions (Medium Transparency)

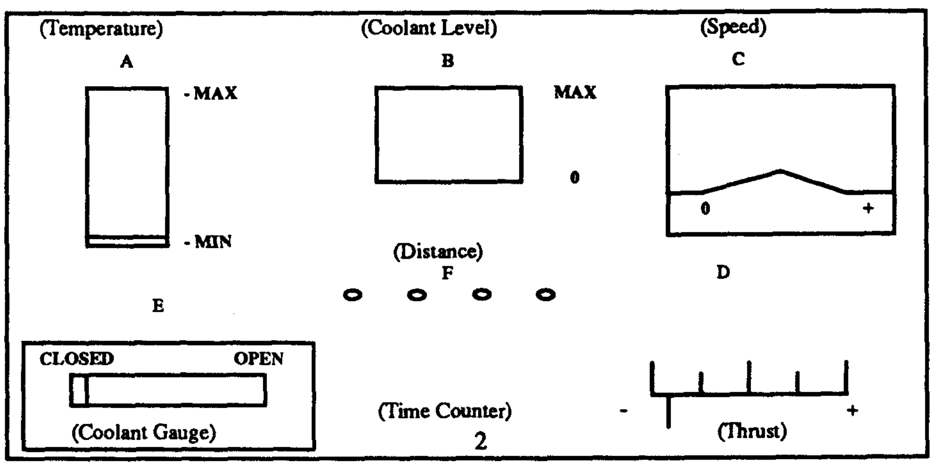
S/D: Similar gauges / Different functions (Low Transparency; cross-mapped condition)

2a.
BASE
(S/S)



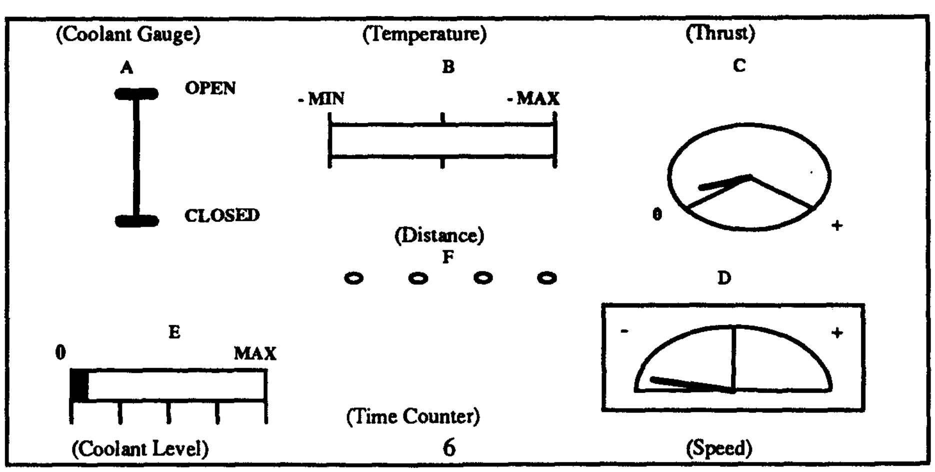
HIGH TRANSPARENCY

2b.
BASE
(D)



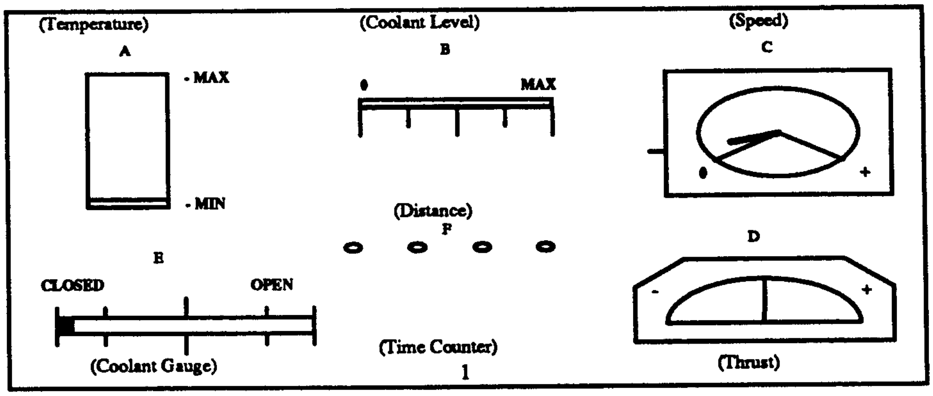
MEDIUM TRANSPARENCY

2c.
BASE
(S/D)



LOW TRANSPARENCY

2b.
BASE
(D)



TARGET

Figure 2. Device Panels

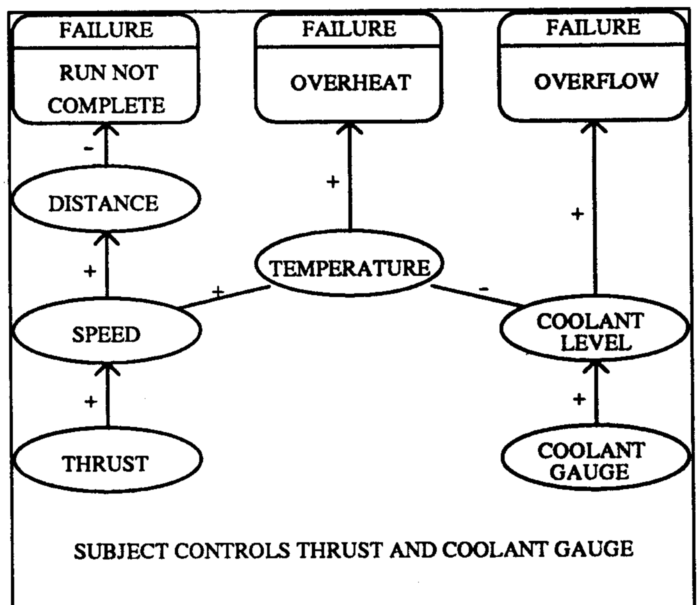


Figure 3. Causal Model of Device Operation

In all cases, the variation in mapping condition was achieved by varying the base device. The target device was identical for all subjects. (This was done to achieve maximum comparability across conditions in the transfer condition.) The three base devices are shown in Figures 2a, 2b and 2c, and the target device is shown in Figure 2d. In the high transparency (S/S) condition, the gauges of the target panel looked like the base gauges (Figure 2a) that had similar functions. In the medium transparency (D) condition (Figure 2b), the target gauges bore (Figure 2d) little or no resemblance to the corresponding base gauges. In the low transparency (S/D) condition (Figure 2c), cross-mapping occured: each target gauge looked like one of the base gauges, but it s function matched that of a different base gauge. Thus any tendency to place the target gauge in correspondence with its look-alike counterpart in the base device would lead to error. This was predicted to be the most difficult mapping condition. In sum, the base devices varied according to systematicity (systematic or non-systematic device model) and mapping condition (S/S, D, or S/D), for a total of six different cells.

Procedure. Subjects were randomly assigned to one of the six groups. They were given an introduction to the experiment and received a sheet of operating instructions on how to run the device. Each gauge was described in terms of its operation and interaction: what other gauges affect it, and which gauges it affects. The operating instructions also set forth the possible run failures, as described below. For both systematic and non-systematic subjects a letter name was used to label the gauge as shown in Figure 2. Additionally, systematic subjects had semantic labels on their instruction sheet for each gauge (e.g., Speed (Gauge C)).[4] The operating instructions given , given the non-systematic subjects, were identical to those given the systematic subjects except for the addition of semantic labels in the systematic condition. For example, the description of the temperature gauge for the subjects in the systematic condition was:

Temperature (Gauge A) is controlled by Speed (Gauge C) and Coolant Level (Gauge B). Speed (Gauge C) acts to increase the level of Temperature (Gauge A). Coolant Level (Gauge B) acts to decrease or hold down the level of Temperature (Gauge A). In other words, Coolant Level (Gauge B) and Speed (Gauge C) work in opposite directions to control Temperature (Gauge A). Do not let Temperature go to its maximum.

For the non-systematic subjects, the description of temperature was:

Gauge A is controlled by Gauge C and Gauge B. Gauge C acts to increase the level of Gauge A. Gauge B acts to decrease or hold down the level of Gauge A. In other words, Gauge B and Gauge C work in opposite directions to control Gauge A. **Do** not let Gauge A go to its maximum.

In addition to the operating instructions, subjects were also given a diagram of the base panel (Figure 2a, 2b or 2c, depending on the subject's mapping condition). They were allowed to keep both the operating instructions and the diagram while operating the device .

After subjects read the information, they learned to operate the base device. On each run subjects could either complete the run successfully or encounter one of three failure conditions (see Figure 3) (1) a coolant overflow, in which the coolant level reached maximum; (2) the device overheated, meaning the temperature gauge reached its maximum; or (3) time out; in which the run was not completed in the specified amount of time (e.g., before the time counter reached maximum). In a failure condition the subject saw a message indicating the nature of the failure. Subjects were considered to have learned the base device when they reached a criterion of three correct trials out of five successive trials.

Target. Upon reaching the learning criterion on the base device, subjects were immediately moved to the target. They were told that it was operated in the same way as the base device. Note that, since the target gauges were always correctly labeled with the same letter labels as the base (i.e., C=Speed, D=Thrust), subjects logically possessed enough

[4]The semantic labels did not appear on the screen. The device panels were identical for systematic and non-systematic subjects and showed only the alphabetic labels.

information to operate the new device perfectly. The question was whether they could use this information. The criterion for learning the target was two correct out of four successive trials.

Target with load. After reaching criterion on the target, subjects were given the load task. This was the same target panel they had just learned, with an auxiliary load task requirement as follows. Every 5 seconds or so a random number would appear, at the same central location on the screen. The subject had to respond by pressing one of two keys within a certain time period. If the subject did not respond correctly on two items of the auxiliary task, the trial was aborted. Subjects received a message indicating auxiliary task failure. The same criterion for success was used as in the original target learning: two correct out of four successive trials.

Each subject was given an hour and fifteen minutes to learn the base device. Subjects who had not reached criterion in that amount of time were removed from the experiment. 18 of 54 subjects were dropped because of this time constraint.

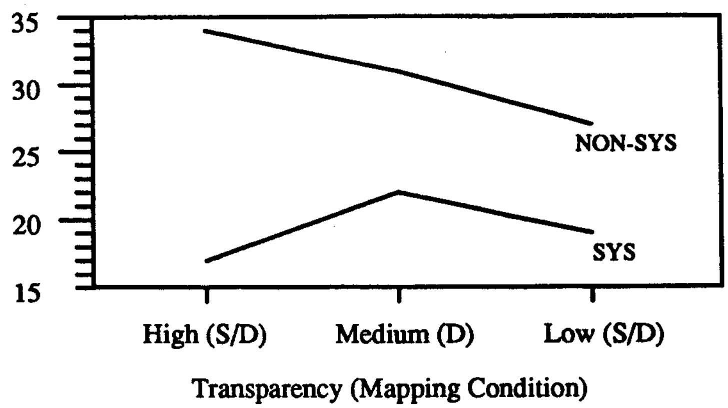
Results

Learning the base.

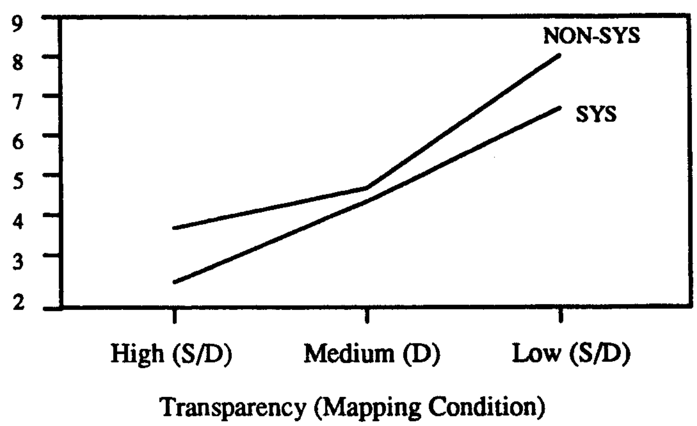
Systematicity had strong effects on the original learning of the base device. As shown in Figure 4a, subjects in the systematic condition required far fewer trials to reach successful criterion than subjects in the non-systematic condition. Using the number of trials to criterion (2 of 4 correct runs) a 2 x 3 (Systematicity (between) X Mapping Condition (between)) analysis of variance (ANOVA) was performed. (Transparency should, of course, have no effect here. Mapping Condition was included as a check to be sure all base devices were equally difficult.) This analysis showed a main effect for Systematicity [$F(1, 30) = 6.575$, $p < .02$] and no effects of the Mapping Condition or the interaction of Systematicity X Mapping Condition. The effect of Systematicity for the base device can be taken as evidence that giving a coherent causal model of a device helps initial learning of the device as in Kieras and Bovair (1984). The lack of a main effect or interaction for Mapping Condition shows that there were no differences in difficulty of the base due to the transparency manipulation.

Transfer to target

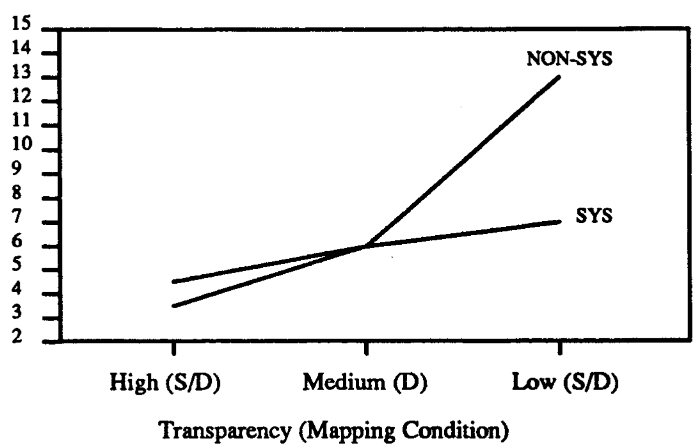
The results are encouraging in part. As Figure 4b shows, transparency had strong effects on transfer difficulty. The more transparent the mapping of component correspondences, the more quickly subjects learned the target. However, we did not find reliable effects of systematicity of the base model even though there is a tendency for subjects in the systematic condition to show greater transfer.



4a. Base



4b Target



4c. Target Load

The dependent measure of difficulty of transfer was the number of trials to reach criterion on the target device. A 2 X 3 ANOVA of Systematicity X Mapping Condition showed a main effect for Mapping Condition [$F(2,30) = 5.673$, $p<.01$]. The Systematicity factor and the interacting of Systematicity X Mapping Condition failed to reach significance. Possibly the results were affected by the high dropout rate and the low number of subjects per cell (6). Further experimentation is planned. Significant results for Mapping Condition confirm that surface correspondences between device components affect transfer of knowledge of one device to another.

Target with load. Mapping Condition had a marginal effect on performance with a load task: As Figure 4c shows the number of trials to criterion decreased with increasing transparency. Although Figure 4c also suggests that systematicity improved transfer, this effect is not statistically significant. Using the number of trials to criterion (3 of 5 correct), and ANOVA showed marginal main effect for Mapping Condition [$F(2,30) = 3.179$, $p<.06$]. Systematicity and the Systematicity X Mapping Condition were not significant. It is possible that these results will be stronger with more subjects per cell.

Discussion

In this research, we found effects of systematicity in the initial learning of an unfamiliar device and of transparency in transferring that knowledge to another device. There was some indication that systematicity might also have effects on device transfer, although the results were not reliable. These results have implications for analogical processing as it applies to device learning and transfer of training.

According to structure-mapping theory, the analogical mapping process involves setting up object correspondences and carrying across predicates. We predicted that two factors would influence the difficulty of the mapping process. The first factor is systematicity - the presence of a coherent causal model of the base that can apply in the target. Having a constraining higher-order relation that governs lower-order predicates should both guide the on-line mapping of lower-order predicates and provide the learner with a way to debug the mapping (Gentner and Toupin, 1986). The second factor is the transparency of the object-correspondences: the greater the surface similarity between the objects in the base and target, the easier it should be to keep the mappings clear. Our current results provide clear support for the second prediction that high transparency improves transfer. For the first factor, our results show that systematicity helps in initial learning of the base, and suggest that systematicity may also help in the mapping process.

This research indicates that having a good mental model at the outset assists learning to operate an unfamiliar device and that low transparency mappings can make transfer to an analogous device considerably more difficult. These results suggest that the distinctions made in mapping are useful in explaining and predicting transfer.

Acknowledgments

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