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An Informational Perspective on Skill Transfer in Human-Machine Systems

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Differentiation of perceptual invariants is proposed as a theoretical approach to explain skill transfer for control at the human-machine interface. I propose that sensitivity to perceptual invariants is enhanced during learning and that this sensitivity forms the basis for transfer of skill from one task to another. The hypothesis implies that detection and discrimination of critical features, patterns, and dimensions of difference are important for learning and for transfer. This account goes beyond other similarity conceptions of transfer. To the extent that those conceptions are specific, they cannot account for effects in which performance is better following training on tasks that are less rather than more similar to the criterion task. In essence, this is a theory about the central role of low-dimensional informational patterns for control of behavior within a high-dimensional environment, and about the adjustment of an actor's sensitivity to changes in those low-dimensional patterns.

INTRODUCTION

An actor will often find a new task easier as a result of prior experience with a different task. This effect, which is referred to as *skill transfer*, suggests that specific skills or capabilities acquired by practice with one task can be employed in the performance of another task. A task may be understood as a problem to be solved or a goal to be achieved. In the research to be reviewed the task will be accomplished via the actor's manipulation of a mechanical or electronic device. The manner in which the task is to be accomplished will be determined by the dynamics of the controlled device and the relationships at the interfaces among actor, device, and environment. Thus the characteristics of the controlled device, the means of activating the system, and knowledge about the nature of the task may all affect transfer.

If two tasks are highly related, there will be high transfer; if they are essentially unrelated, there will be no transfer. In some circumstances transfer can be negative—that is, performance on the transfer task will be poorer than if there had been no pretraining at all. This occurs when the tasks are related but differ radically in some critical aspect. In other circumstances prior experience with a special training task can result in better performance than would equivalent prior training with the transfer task itself. Thus transfer can be enhanced by the use in training of carefully planned distortions of the criterion task.

The goal of this paper is to develop an ac-

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count that will form the basis for understanding skill transfer at the human-machine interface. That goal is pursued primarily by a review and analysis of research from the task domain of manual control (i.e., tracking or vehicular control), but observations are offered on how the insights derived from this analysis could be applied to a wider range of tasks. Established approaches to skill transfer are first reviewed. These do not provide a satisfactory account of existing data or useful guidance for researchers and training specialists. A contrasting informational perspective is developed around the concept of a perceptual invariant as introduced by J. J. Gibson (1979). This perspective is then applied to a set of transfer data from the manual control literature. Ideas drawn from the perceptual differentiation theory of E. J. Gibson (1969) are used to develop a description of a learning process that is consistent with the informational perspective.

SIMILARITY AND TRANSFER

It is self-evident that skill transfer is based on some type of similarity between training experience and operational experience. That idea has been prevalent at least since Thorndike (1903) formulated his law of identical elements. The basic notion is that transfer between two tasks will occur to the extent that they share common components, even though they may differ in many other respects. In applied training environments some notion such as similarity to the operational task or quantity of fidelity is often invoked to justify trainer design features. This approach has, for example, dominated discussion of motion and visual systems for flight simulators (Comstock, 1984; Cyrus, 1978; Needham, Edwards, and Prather, 1980; Spooner, Chambers, and Stevenson, 1980).

A contemporary cognitive-based justification of the high-fidelity approach may be found in the instance memory theory of skilled behavior put forth by Logan (1988a, 1988b). In that theory each experience with an event establishes an episodic memory trace. There is stochastic variability for recall speed of individual traces, so that as the number of stored traces for a specific behavioral activity increases, performance becomes more skilled because there is an increase in the likelihood of quickly retrieving an appropriate trace. One strong implication of instance memory theory is that training situations should be as similar as possible to those encountered in the field (Logan, 1988a, p. 590). The emphasis would be on fidelity in both training programs and training devices.

Nevertheless, this account does not acknowledge that some dimensions of fidelity do not contribute to transfer effectiveness. Few would argue, for example, that transfer is enhanced if the color of an aircraft and its companion simulator are identical. A cognitive theory might specify that the attention-demanding aspects of the task are the ones that need to be faithfully represented in the training environment (G. D. Logan, personal communication, June 1990). In applied training circles, appeals to psychological fidelity (Goldstein, 1986) or functional equivalence (Baudhuin, 1987) imply recognition of the fact that some identities are irrelevant to transfer. Although these notions may constitute some progress in relation to a naive view of similarity, they do not offer a specific statement about the similarities that are important.

From another perspective, similarity and fidelity theories fail because some data show better transfer if the training task differs on specific dimensions from the criterion or transfer task. For example, the addition of visual augmented feedback can speed acquisition of landing skill in an aircraft simulator (Lintern, 1980), and transfer to crosswind landings is actually better if no crosswind is used in training (Lintern, Roscoe, and Sivier, 1990). Wightman and Sistrunk (1987), in an investigation of part-task training for teaching carrier landings, have shown that a backward-chaining procedure can enhance transfer to the whole task. In these experiments deliberate departures from similarity actually enhanced transfer to the criterion task.

More generally, the exploration of special instructional strategies is based on the assumption that transfer will not be degraded and may be enhanced by planned departures from similarity (Lintern, 1989; Wightman and Lintern, 1985). Thus similarity, as it is normally viewed, is not a sufficient element of a conceptual approach to skill transfer. The challenge remains to formalize the notion of similarity in some way that will account for skill transfer effects and that will permit useful exploitation of that notion in applied training programs. The success of this endeavor depends on distinguishing identities that are critical to transfer from those that are irrelevant.

One approach to distinguishing dimensions of similarity can be found in the response surface proposed by Osgood (1949). Although that surface was modeled entirely on the basis of verbal learning research, Holding (1976) reviewed it for its applicability to action skills. Holding's model indicates that maximum stimulus and response similarity should yield maximum positive transfer but that variation in stimuli will not always degrade transfer. However, the distinction between stimulus and response is not easily sustained in manual control or in many other action skills in which responses generate important perceptual information.

Gick and Holyoak (1987) have developed a theory of cognitive transfer for verbal skills in which rules constitute the elements that are transferred. Those rules are generally explicit, which cannot account for manual control, but there are implicit rules as well. Presumably the abstract rules central to Schmidt's (1975) motor skill theory are also implicit. In that theory the rules are incorporated into generalized motor programs that guide behavior. Thus similarity for transfer could be embodied in common motor programs or implicit rules. Motor program or rule-based views might explain data that show that some identities are irrelevant to transfer (and also explain those data that show better transfer from less similar tasks) in terms of how well the rules or programs are established by the training conditions (Schmidt and Young, 1987). However, the type of task-related information that leads to development of a rule or motor program is not specified. Learning principles that could account for the transfer effects to be found in the domain of manual control also remain unspecified. It is the nature of that information and of the learning principles that is the focus of this paper.

INFORMATIONAL INVARIANTS

The transfer perspective developed here draws on the ecological theory of perception as developed by J. J. Gibson (1979). I argue that manual control skills are supported by information derived from critical relationships in the task environment. Such relationships have specific values that remain invariant while the actor is performing correctly but which have different values when he or she is performing poorly. With aircraft landings, for example, one or more relationships will be invariant if the pilot remains on the designated approach glide slope. Those relationships will change, however, if the pilot deviates from the designated glide slope, and the pilot's ability to recognize that deviation and to correct for it depends on his or her sensitivity to changes in the relationships that specify correct or accurate control.

Gibson (1979) characterizes such relationships as *invariants*. Within a changing sea of information, the individual character of an event will be perceived because of some specifiable property or relational value. That property or relation will remain constant across events that are perceived as similar but will differ between events that are perceived as different. Thus an invariant is a property of an event that remains unchanged as other properties change: that which specifies the persistent character of the event (Gibson, 1979). Following Stoffregen and Riccio (1988), it may be viewed as a lawful relationship between patterns of stimulation and properties of the task.

A complete description of any natural state or event would require reference to enormous, even infinite, detail. One useful strategy for a scientific endeavor is to reduce the infinite detail in the domain of inquiry to a succinct and meaningful description—that is, to offer a low-dimensional description of nature (Feynman, 1967). Any characterization by way of invariants is a low-dimensional description of a high-dimensional event. Because invariants distinguish differences and link identities (Cutting, 1986), they may provide an appropriate low-dimensional basis for a theory of transfer.

Reference to an intriguing demonstration by Johansson (1973) will illustrate the power of invariants. His observers viewed a set of lights that were located on the main joints of an otherwise invisible human's limbs. While the human was stationary the lights appeared as a random assemblage, but the nature of the activity and the fact that it was generated by a human could be perceived if that human engaged in activities such as walking or hopping. At the cessation of activity the lights again appeared as a random assemblage. The manner in which the lights changed relative to one another in time and space specified the activity and the humanness of the actor. Within the experimental literature this effect is referred to as *biological motion.*

Invariants for Perception

Not all invariants are functional. It is often possible to identify relationships that meet the formal requirements but which have no effect on behavior, perhaps because the changes that correspond to changes in an event are below threshold or because a different invariant is selected by the observer (Cutting, 1986). One important challenge for perceptual research is to identify functional invariants (those that support perceptual judgments).

Cutting (1986) has argued that some perceptual judgments can be supported by cross ratios formed from the spatial separation of elements within objects. For example, a ratio formed from the distances among elements on a rotating surface will be invariant if the surface is rigid but not otherwise. This cross ratio might be used for judgments of rigidity, and Cutting's data verify that hypothesis. Invariants for judgment of "time to contact"—that is, the time that will elapse before an approaching object will reach an observer (Lee, 1976; Lee, Young, Reddish, Lough, and Clayton, 1983)—and those that support judgments pertaining to the ballistic trajectory of a ball (Todd, 1981) have also been specified analytically and shown to affect perceptual judgments.

Even the seemingly complex phenomenon of biological motion might succumb to analysis by way of invariants. Cutting, Profitt, and Kozlowski (1978) have argued that the perception of biological motion is based on information about centers of moment. All rigid objects that move in contact with the ground have at least one center of rotation about which the motions of other elements on the rigid object move in arcs. For complex, multisegmented objects there will be multiple centers of moment. During motion, rotations around the centers of moment are symmetric and periodic. Centers of moment for the human body can be calculated on the basis of sizes of body parts. Cutting et al. (1978) showed how centers of moment can account for many puzzling biological motion effects, such as the ability to detect walking motion merely from ankle movements and the ability to distinguish male from female walkers. Centers of moment appear to offer a useful basis for a low-dimensional description of complex, high-dimensional events.

THE CONTROL OF ACTION

For J. J. Gibson's ecological psychology, invariants provide the information for action; in other words, the control of action is informed by perceptual invariants (Gibson, 1958). The term *visual kinesthesis* refers to the fact that moving observers coordinate their behavior with visual information from the environment. That information will be specific to the layout or the structural properties of the environment and also to relative motions or kinematic properties generated by an observer's own actions. The emphasis in this paper is on manual control—that is, the operation of dynamic, interactive control systems such as vehicles, vehicle simulators, and laboratory tracking systems. As a subcategory of human action it should be amenable to the type of analysis recommended by Gibson.

Invariants for Manual Control

For invariants to be of use in a theory of human action, it must be possible to isolate them analytically and to test their effects on behavior. An invariant to judge the speed of self-motion might be derived from the rate of optic flow. Where speed and distance to visible surfaces remain constant, the relative rate at which visible elements in a scene pass by a moving observer will generally be constant. The perceived invariance of flow can, however, be disrupted by inhomogeneity of element distribution. Denton (1980) evaluated the influence of this latter factor in a driving simulator with a visual display. Pattern distortions in which elements became more compressed throughout a trial caused subjects to reduce their simulated speed despite instructions to keep it constant. This experiment indicates that an invariant relative rate of visual flow can be used to maintain velocity and that distortions of the invariant will have predictable effects.

Mertens (1981) has examined the information available for aircraft landings. He identified the form ratio (the ratio of projected runway length to projected breath of the distant end of the runway) as an invariant that might support landings. Distortions of this ratio within a simulator were shown to bias the glide slope judgments of experienced pilots in the expected direction. Although we are as yet a considerable distance from accounting for the full range of human behavior by analysis of the relevant invariants, the studies of Denton (1980) and of Mertens (1981) indicate that perceptual invariants can be isolated analytically and that their effects on behavior can be demonstrated.

An Invariant for Transfer

A contrast between experiments by Gordon (1959) and Briggs and Rockway (1966), in which transfer was tested from pursuit to compensatory and from compensatory to pursuit displays, suggests that an invariant for the transfer of manual control skills may be found within a regular or predictable forcing function. A pursuit display is one in which a cursor, under the control of the actor, is used to track a target that is disturbed by a forcing function. A compensatory display has only one moving cursor, and the actor's task is to maintain it at a fixed target position while it is being disturbed by a forcing function. In these two experiments subjects were trained with either a pursuit or a compensatory task, and in transfer they either continued with their training task or switched to the alternative version of the task.

Gordon (1959) used a simple cloverleaf pattern for the tracking course. Tracking in the pursuit mode was generally better than tracking in the compensatory mode (Figure 1). In transfer from pursuit to compensatory tracking, performance initially regressed to a level obtained from subjects who had first trained with and then continued with compensatory tracking, but it improved quickly toward a level obtained from subjects who were now tracking the pursuit task. This result suggests that pursuit training is better for compensatory tracking than is an equivalent amount of compensatory training.

Briggs and Rockway (1966) used a more complex pattern for their tracking course (the sum of 0.092-Hz, 0.153-Hz, and 0.247-Hz sine waves). Although there were clear differences between pursuit and compensatory performances in both training and transfer, there were no large differential effects on transfer to either display as a function of the training manipulation (Figure 2). In particular, those transferring to pursuit from compensatory tracking did not perform better than did those who tracked with the compensatory system throughout. Apparently Gordon's subjects could better learn skills required for compensatory tracking from practice on a pursuit task than from practice on a compensatory task, but Briggs and Rockway's could not.

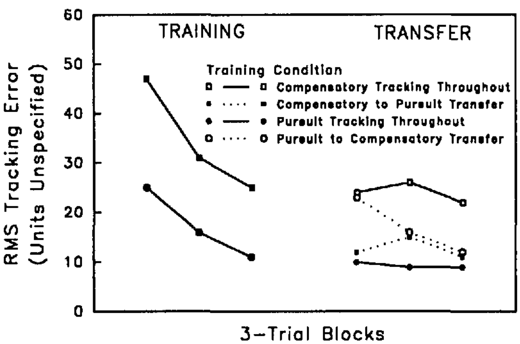

Figure 1. *Transfer between pursuit and compensatory displays with a simple course. Half of the subjects from each training group transferred to the alternative condition. (Adapted from Gordon, 1959.)*

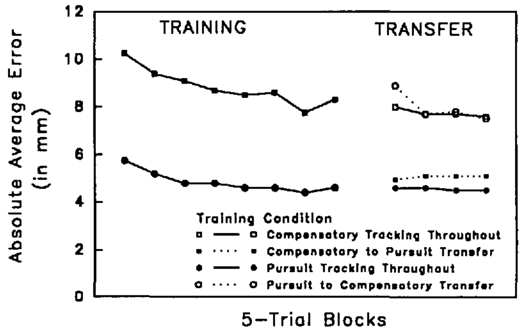

Figure 2. *Transfer between pursuit and compensatory displays with a complex course. Half of the subjects from each training group transferred to the alternative condition. (Adapted from Briggs and Rockway, 1966.)*

Given the differences between experimental apparatus and procedures in these two experiments, any statement about the differences in results must remain speculative. Nevertheless, within the terms of the theory outlined here, these contrasting results may be understood by considering the difference between pursuit and compensatory tracking and the differences in course complexity of the different tracking systems. Compensatory displays almost always present a more difficult task than do pursuit displays, in large part because effects of the disturbance or course cannot be distinguished visually from control effects. A compensatory display will increase the difficulty an actor has in visually differentiating the effects on system behavior of control movements and a disturbance. Thus an actor is unlikely to acquire sensitivity to repeating regularities in the forcing function as quickly with a compensatory display as with a pursuit display. If, however, sensitivity to these regularities could be acquired during pursuit tracking, subsequent performance on the compensatory version of the task should be enhanced.

Considering the relatively small amounts of practice allowed in each of these experiments, practice with the pursuit version of the task could have established awareness of the regularities in the relatively simple cloverleaf pattern used by Gordon but not of the more complex sum-of-sines pattern used by Briggs and Rockway. This contrast between the two experiments implicates the pattern of the course as an important factor in transfer. In terms of invariants it is a low-dimensional relationship within the pattern that is critical.

The view of an invariant as a low-dimensional description of a high-dimensional event is important. Any discussion of an invariant as a high-dimensional description of a high-dimensional event would render the concept superfluous and would constitute a high-fidelity theory of transfer. The episodic memory trace of instance theory (Logan, 1988a), being a copy of an event, is a high-dimensional representation of that event. Instance theory is not consistent with the view that low-dimensional invariants support transfer. One relatively straightforward interpretation of Gordon's data, which is consistent with Logan's (1988a) theory, is that subjects had learned all details of the pattern; that is, they had learned to exploit a high-dimensional description of the critical information. In contrast, perceptual invariants such as cross ratios (Cutting, 1986), form ratios (Mertens, 1981), and centers of moment (Cutting et al., 1978) are of a low-dimensional form. To be consistent with the concept of invariants, it must be possible to develop a low-dimensional description of a forcing function which specifies the relationships essential for transfer.

Schmidt and Young (1987) argued that it is the timing relationships in a patterned response that remain invariant. Thus a low-dimensional description of a pattern to be followed in a tracking task is more likely to be based in the temporal relationships between adjustments in control actions than in the amplitudes or total duration of those actions. The results of two pursuit rotor experiments (Lordahl and Archer, 1958; Namikas and Archer, 1960) bear on this issue. Subjects were transferred from high or low speeds to moderate speeds of rotation or from high or low amplitudes to moderate amplitudes of rotation. A penalty was incurred in transfer to a new speed of rotation but not to a new amplitude of rotation. Because speed and amplitude of rotation represent frequency and amplitude of the forcing function, these results suggest that the functional invariant is related to frequency but not to amplitude. These data suggest that a low-dimensional description of the similarity underlying transfer might be based in the timing relationships of the course, and that a fully detailed description is not required for transfer.

Environmental Information

One implication of the hypothesis outlined for this paper is that natural environments contain structural information to guide behavior. In a test of this notion, Lintern et al. (1990) used a light aircraft simulator to teach flight-naive subjects to land. Training was conducted either with a pictorial representation of a normal airport scene or with a symbolic display that guided subjects through the required maneuver but offered no realistic representation of any natural or cultural features. The two groups performed equally well in training, but those trained on the symbolic display performed poorly in transfer (Figure 3). Although the specific nature of the information that guided behavior was not isolated in this experiment, low-dimensional relationships such as form ratio (Mertens, 1981), projected aimpoint-to-horizon distance (i.e., the distance between the runway aimpoint and the horizon projected onto a

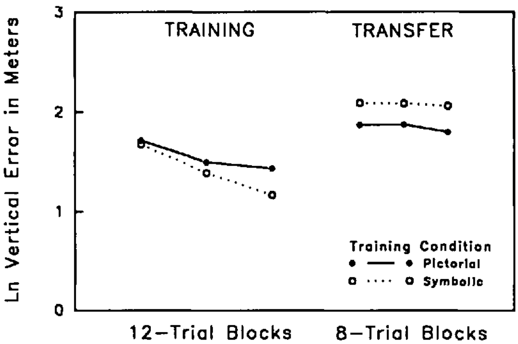

Figure 3. *Transfer of aircraft landing skills from a symbolic or pictorial display. In transfer, subjects were required to execute an approach, roundout, flare, and touchdown to a display identical to that used for the pictorial training group. (Adapted from Lintern et al., 1990.)*

plane at some arbitrary distance in front of the pilot and perpendicular to the line of sight; Langewiesche, 1944), or horizon-aimpoint angle (Lintern and Liu, in press) to be found in a pictorial scene might perform that function.

LEARNING AS DIFFERENTIATION

In the discussion so far I have advanced claims about the nature of what is learned during acquisition of an action skill but have referred only tangentially to the learning process. For example, I argued that Gordon's (1959) subjects learned invariant relationships within the forcing function more effectively in the pursuit tracking mode because the pattern of the course was more perceptible. It will now be useful to consider the nature of learning in more depth. A view of learning consistent with the informational perspective is that of perceptual differentiation, a process by which information becomes more discriminable (E. J. Gibson, 1969). Being a process whereby what was once perceived as the same is now perceived as different, it is analogous to cellular biology, where *differentiation* refers to the process by which formerly identical cells acquire unique characteristics.

Perceptual thresholds are central to any theory of perception based on invariants because without reference to thresholds, there is no reference to the capabilities of the actor (Cutting, 1986). An actor must be able to perceive changes in perceptual information that is to be held invariant during execution of a task, and the concept of threshold is employed to account for the fact that the perceptual resolution of such changes is finite. The perceptual differentiation hypothesis implies that an actor's difference thresholds for recognition of changes or patterns in the workspace can be lowered through experience. There is a progressive development of the actor's sensitivity to constancies within tasks and differences between them. Learning moves through a course of progressively finer discriminations of important information, and regularities become informative via processes leading to differentiation along dimensions of variation. Previously vague impressions become increasingly specific as they relate to task requirements. From this perspective skilled behavior must exploit perceptual information, and skill develops via a process of becoming sensitive to it.

In her discussion of differentiation, E. J. Gibson (1969) emphasized objects and events in the environment external to the observer. At the human-machine interface there is a wider range of concerns. Here learning will involve the increasing differentiation of previously confusable information, which may reside in any element of the task environment, even in response production. The difference between skilled and unskilled behavior can therefore be at least partially characterized as differential sensitivity to task-related information.

Gibson's (1969) review suggests that certain instructional techniques speed differentiation, particularly those that draw attention to the distinguishing perceptual invariants. Techniques that contrast different values of distinguishing properties, abstract them, or accentuate them should be useful. In some cases it may help to offer advice about what to look for (Biederman and Shiffrar, 1987). Nevertheless, even highly skilled actors are often unaware of the information they use to support their own activities, and it is unlikely that much of the information for skilled activity is sufficiently explicit for that type of instruction. Implicit information might be learned more readily via special instructional techniques that enhance or clarify it. Additionally, anything that conceals or diverts attention from critical information will impede the differentiation process.

DIFFERENTIATION FOR MANUAL CONTROL

Established theories of transfer cannot account for those effects that show enhanced transfer from less similar training. Asymmetric transfer of this type has already been encountered in the study by Gordon (1959). As is consistent with the differentiation view, the pursuit display appears to have clarified the pattern of the course to be followed. That clearer presentation enhanced learning of critical invariants, which then resulted in superior control. The experiments reviewed in the following sections demonstrate similar asymmetric effects.

Augmented Feedback

A number of manual control experiments have examined the use of supplementary visual or auditory information during training. The supplementary information is used to provide on-line feedback to subjects during their performance of the task. The data from these experiments do not always favor the use of augmented feedback. Several experiments have shown that it can speed acquisition of the task and enhance transfer to nonaugmented conditions, whereas others have shown no differential effect in transfer to nonaugmented conditions, or sometimes even a decrement. From an analysis of approximately 30 tracking studies, Lintern and Roscoe (1980) argued that the effectiveness of augmented feedback training appears to depend critically on some characteristics of the task and on how the supplementary feedback was presented.

In many early studies the supplementary feedback was presented when the subjects were tracking correctly. The data tended to show a strong performance advantage during training but no transfer advantage. Occasionally the training advantage reversed in transfer so that the loss of supplementary cues appeared to set subjects back further than if they had practiced with a nonaugmented condition. Lintern and Roscoe (1980) argued that subjects who became dependent on augmenting information would not perform well in its absence. In terms of the differentiation hypothesis, augmenting information may distract attention from some task-related invariants that offer a significant learning challenge.

Later studies presented the supplementary feedback when subjects were tracking incorrectly, and it has usually been this manipulation that has shown transfer benefits from training with augmented feedback. The contrast between augmented feedback conditions that show positive differential transfer and those that do not suggests some insights about differentiation of perceptual invariants in manual skill. In particular, it seems that an off-target augmentation would not distract attention from critical invariants that specify correct performance or that would support accurate tracking. In contrast, on-target information is likely to distract attention from at least some of the critical invariants. Even when enhanced transfer is found following training with on-target augmentation, the enhancement is usually not as strong as that obtained with off-target augmentation (e.g., Williams and Briggs, 1962).

Two studies, one by Kinkade (1963) and the other by Williams and Briggs (1962), are particularly informative for the differentiation hypothesis. Kinkade (1963) examined the effects of visual noise (random, high-frequency, two-dimensional movements of the cursor) and augmented feedback (supplied by auditory clicks when the subjects were tracking correctly) on the acquisition of skill with a compensatory tracking task. A relatively simple forcing function (the sum of 0.1-Hz and 0.2-Hz sine waves) was used. When present, the noise was superimposed on the forcing function. Its maximum amplitude was approximately one-third the maximum amplitude of the forcing function. The visual noise conditions of training (either some or none) were continued without change in transfer. For no visual noise, augmented feedback training helped performance in training and in transfer to no augmentation (Figure 4). Thus it appears that augmented feedback can serve to clarify invariants of the forcing function except when the regularities in that forcing function are obscured by a confounding influence such as noise.

Williams and Briggs (1962) used the same apparatus (and forcing function) and no-noise condition used by Kinkade. In addition to the control and on-target augmented feedback conditions tested by Kinkade, they examined off-target augmented feedback. Training with augmented feedback produced a transfer benefit to nonaugmented conditions, but the benefit from the off-target schedule was greater than from the on-target schedule (Figure 5). The implication of this experiment is that although augmented feedback may enhance differentiation of course-related invariants by encouraging subjects to reproduce the correct tracking pattern, there is also some potential for it to mask or distract attention from those invariants. In this case those subjects trained in the on-target condition may have come to depend at least partly on the augmenting information to inform them when they were tracking correctly.

More generally, it seems important for skill acquisition that subjects attend to the natural task invariants when they are tracking correctly in order to promote sensitivity to the range of invariant information that supports correct performance. Thus augmented feedback provided when the subject is tracking correctly may divert attention to artificial

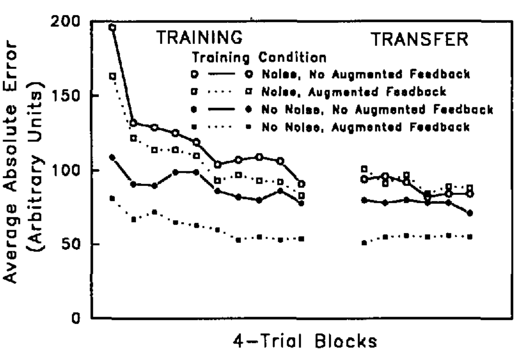

Figure 4. *Effects of augmented feedback on transfer of a continuous tracking task. Visual noise was included as a nontransfer variable. (Adapted from Kinkade, 1963.)*

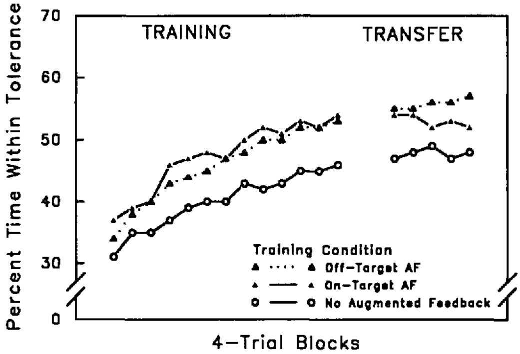

Figure 5. *Effects of augmented feedback on transfer of a continuous tracking task. All subjects transferred to a nonaugmented condition. (Adapted from Williams and Briggs, 1962.)*

information. In contrast, off-target augmented feedback can serve to guide the subject back to correct performance and thereby increase opportunities for attending to the information that specifies correct performance, but it should not divert attention from the information that specifies accurate control.

Nevertheless, on-target augmentation is not always detrimental to transfer (Kinkade, 1963; Williams and Briggs, 1962). Lintern (1980) postulated that the tendency for on-target augmenting information to mask or distract attention from those invariants that specify the actual state of the controlled cursor (or vehicle) will be accentuated to the extent that the normal information of this type is obscure or less compelling. Thus the advantage of off-target augmenting feedback over on-target (and continuous) augmenting feedback would be enhanced when the task-related invariants are obscure because the tendency for the supplementary information to attract attention would be stronger.

In a test of this notion, subjects were taught to land a light aircraft simulator. The difficulties with landing experienced by a beginning student are primarily attributable to the obscurity of the information that can be used to guide the aircraft along the correct approach path (Langewiesche, 1944). Training was conducted with continuous, off-target, or no augmented feedback. Both types of augmentation helped training performance, but only the advantage accruing from the off-target schedule carried over to the transfer test with no augmented feedback. Thus this experiment supports the hypothesis that some forms of augmentation will impede learning of perceptual invariants that are obscure. It also emphasizes the need to acquire skill with invariants that specify current device state in relation to its desired state. One such invariant is the horizon-aimpoint angle, which has been shown to affect glide slope performance of experienced pilots (Lintern and Liu, in press).

Clarification of System Response

Two other flight training experiments are also relevant to the argument developed here. In the first, Lintern, Thomley-Yates, Nelson, and Roscoe (1987) taught military pilots a visually supported bombing skill in a flight simulator with either a relatively detailed pictorial scene or a grid pattern. Those trained on the pictorial scene performed better on subsequent transfer to the grid pattern than did those trained with the grid pattern itself. In the second experiment Lintern et al. (1990) used a light aircraft simulator to teach crosswind landings to flight-naive subjects. Some subjects were trained with no crosswind and others were trained with 5 knots of crosswind. On transfer to a 5-knot crosswind condition, those subjects trained without crosswind performed better than did those subjects trained with it.

From the informational perspective it can be argued that the better visual information provided by Lintern et al. (1987) in the more detailed scene clarified the relationships between control actions and system response. In the experiment of Lintern et al. (1990), the presence of crosswind during training would confound perception of the relationships between control actions and system response, thereby slowing learning of critical invariants related to system control. Thus data from both experiments suggest that clarification of system response will lead to more effective learning of kinematic invariants associated with dynamic control.

DISCUSSION

The transfer observed following training on a task that differs in some specific respects from the criterion task is often better than transfer observed following equivalent training on the criterion task itself. The informational account offered here is, to my knowledge, the first synthesis of such transfer effects. From an identical elements perspective (Thorndike, 1903), an instance memory perspective (Logan, 1988a), or a response versus stimulus similarity perspective (Holding, 1976), those transfer effects must be viewed as atypical phenomena. In contrast, the appeal to informational invariants forms a basis for a detailed characterization of the task and, when combined with the differentiation hypothesis, one that provides a theoretical account within which these puzzling transfer data become explicable.

The development of a coherent account of skill transfer has proved to be a struggle throughout the past century of psychological and educational research. Commencing with the notion of formal discipline (Woodrow, 1927), a variety of views have emerged, none of which has been able to provide an account that offers a clear research agenda or comprehensive training principles. Major training research programs are sometimes planned under the explicit assumption that contemporary theory should be ignored (e.g., Donchin, 1989). At other times research programs are built around such limited tasks that their relevance to common human activity is questionable (e.g., Logan, 1988b). Reviews of transfer research tend to emphasize behavioral outcomes and also to lament obvious deficiencies but offer little in the way of solid theoretical integration (e.g., Baldwin and Ford, 1988; Briggs, 1969; Lintern and Gopher, 1978; Wightman and Lintern, 1985). The account put forth here constitutes an attempt to resolve these problems. Although the emphasis has been on transfer in manual control, J. J. Gibson's ecological theory is posed as an account of normal human activity. Thus the informational perspective should be relevant to issues of skill transfer with all types of human-machine systems that are of concern in the field of human factors.

Invariants as a Basis for Transfer

The central claim put forth in this paper is that transfer can occur only when critical similarities are maintained across the training and transfer tasks. I have argued that informational invariants constitute properties that define critical similarities and that they are essential components of all tasks that can be learned. If critical invariants (specifically, those that pose a meaningful learning challenge) remain unchanged, transfer will be high even when many other features of the environment, context, or task are changed. The learning aspect of this theory was described in terms of differentiation, a process whereby perceptual thresholds are modified. If an operator's perceptual sensitivity to critical invariants can be improved, that enhanced sensitivity will serve to facilitate transfer. A basic assumption of this discussion is that initial contact with any unnatural control environment will almost invariably require the development of sensitivity to new invariants.

According to E. J. Gibson (1969), procedures that accentuate invariants to be learned will enhance differentiation. Thus clarification or enhancement of invariants that offer a significant learning challenge—such as those associated with a pattern within a forcing function, complex control-display relationships, or relationships between informational properties in the environment and the desired state of the controlled system—will speed skill acquisition. The concealment or distortion during training of those critical invariants will actually impede learning. On the other hand, emphasis on invariants that are already well learned, easily learned, or nonfunctional will not affect transfer.

Transfer Theory

There are points of contact with other theories, but one implication of the informational account outlined here is that other attempts to account for transfer of skill through an appeal to some conception of similarity are either incomplete or inadequate. This account shares with Logan's (1988b) instance memory theory a concern with information from an actor's environment but differs in its emphasis on low-dimensional properties of that environment. It also has something of the character of the response surfaces developed by Osgood (1949) and Holding (1976) but offers a different conceptualization of the task features that must be considered.

In that it could be viewed as an account of the information that is internalized as a motor program or a rule, this informational theory might be seen to complement internal process theories, such as the rule-based approach of Gick and Holyoak (1987) or the motor-program approach of Schmidt and Young (1987). That view is not, however, consistent with the ecological program of J. J. Gibson (1979). From the ecological perspective, an appeal to rules or motor programs adds nothing in the way of explanatory power and constitutes little more than an alternative description of observable properties in behavior or in the environment. Such an appeal does not offer a more parsimonious, more general, or more fundamental description, nor does it offer an explanation (Gibson, 1973, 1976).

Nevertheless, some form of change or reorganization internal to the actor is accomplished during learning. A clear understanding of that change or reorganization would, in all likelihood, contribute considerably to our understanding of skill transfer. There is, however, no consensus among behavioral scientists about how to characterize that change or even about the scientific strategy that is most likely to reveal it. The most common strategy—to postulate a hypothetical construct that appears to account for important data trends—raises a serious difficulty for a theory of transfer. Although implications for transfer can be drawn from a hypothetical construct, failure to find the anticipated effects can be accommodated by adjustment of the theoretical formulation. As is evident within the general field of cognitive psychology, endless variations on hypothetical constructs can be forwarded to account for diverse effects.

In the current context the ecological critique amounts to a claim that an internal process, if rigorously specified, will be defined in terms of objective informational properties to be found in the actor-task environment. In that case the postulated internal process adds nothing useful to the informational account. A less rigorous specification of internal process will rely heavily on hypothetical constructs that cannot be evaluated directly and that provide nothing in the way of compelling predictions. Circularity becomes a significant problem in that a transfer construct (e.g., functional equivalence, motor program) can be specified only in terms of behavioral data that the construct is presumed to explain.

In contrast, information is derived from real properties in the task environment. Those properties can be measured objectively and can be distorted, enhanced, or removed. An appropriate task analysis should reveal the relevant informational invariants and provide specific predictions relating to the effects of adjusting that information. J. J. Gibson's ecological program places a heavy burden on the scientist to identify the informational properties that affect behavior. For transfer theory, specification of informational invariants that support transfer is a central requirement. From the ecological perspective, success in that regard will provide considerably more insight into the complexities of skill transfer than will any amount of theorizing about internal process or structure.

Transfer Research

There has been considerable confusion about transfer because experiments that should be able to demonstrate it often do not. There is generally only a vague notion of what can be transferred and what might promote that transfer. The informational perspective suggests a strategy that should correct this unsatisfactory situation. In terms of this perspective it should be possible to specify by analysis the information that is expected to support transfer. It should then be possible to demonstrate predictable performance effects of distorting or concealing that information. It should also be possible to demonstrate predictable effects on transfer of specialized pretraining with that information in isolation or of pretraining on the whole task with that information distorted or concealed.

Specifically, for a task such as landing a light aircraft, it should be possible to identify structural relationships in the environment which specify whether or not the pilot is maintaining correct lineup and glide slope. The horizon-aimpoint angle is one such invariant property that is used for glide slope control (Lintern and Liu, in press). It should also be possible to identify dynamic relationships within the flight control system which specify whether or not the pilot has stable control over the aircraft. Speed of system response to control inputs is likely to incorporate one invariant relationship critical for transfer (Lintern and Garrison, in press). Beginning flight students may already be sensitive to some important invariants, but if the task poses a significant learning challenge, at least some invariants will not be perceived well, and sensitivity to them will have to be enhanced through instruction and practice. It is those invariants that must be identified and assessed in terms of their effect on transfer. More generally, the challenge for transfer research is to identify informational invariants by analysis, to demonstrate their effect on behavior, and to assess their effects on transfer.

Issues for Applied Training

It should be apparent from consideration of the data reviewed in this paper that the development of a training system requires a detailed analysis of the tasks to be learned. As a first step, invariant relationships that support transfer must be identified and faithfully reproduced in a training system. In the design of a flight simulator, for example, faithful representation of the horizon-aimpoint angle may be critical (e.g., Lintern and Liu, in press). It is not uncommon, however—especially when inexpensive computers are used for the generation of a visual display—to model a relatively small world. That results in a distorted horizon-aimpoint angle that does not remain invariant for a constant angle of a landing approach and which, by the perspective offered here, is likely to compromise transfer effectiveness.

Considering that we know little about invariants that support behavior, nothing presented in the development of this theory should be taken as implying that identification of relevant informational invariants is straightforward. The few data that have emerged from research stimulated by J. J. Gibson's ecological program indicate that invariants will be based in abstract relationships (Lintern and Liu, in press; Mark, 1987; Warren and Whang, 1987). The results of the biological motion research suggest that invariants will be discovered in unexpected forms—in particular, ones that are not well anticipated by the bulk of the traditional research on perceptual issues. Identification of critical perceptual invariants is likely to pose a continuing challenge for designers of instructional programs and devices.

Once the relevant invariants have been identified and represented appropriately in the training system, a second step is to implement instructional strategies that will speed their learning. There is at least some indication in the research discussed here of the types of instructional principles that could be useful. From the review of E. J. Gibson (1969), clarification and accentuation seem to be important principles. It will, however, require careful evaluation to verify that these types of strategies can be extended to the diversity of complex tasks found in operational human-machine systems and to tune them for maximum effectiveness in specific circumstances. Thus considerable work remains before the implications of this theory can be readily transferred to operational training. Nevertheless, the promise is that a systematic development of the concepts presented here can, in the long term, have a substantial effect on training effectiveness.

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