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ABSTRACT

This paper describes and critically analyzes several perspectives on interaction and computer technology, examines dimensions of interactions, and presents a framework for the design of interaction strategies. Traditional perspectives on interaction discussed are the operational and the functional. The operational perspective is described in terms of its four components: physical response, feedback based on the response, mental task, and the symbols or codes used to convey information. The functional perspective is described under five headings: supporting lesson pacing, providing the opportunity to elaborate, confirming the accuracy of responses, navigating within or across lessons or lesson segments, and supporting inquiries. The need for a perspective that integrates the operational and functional perspectives is described, associated cognitive and physical responses are outlined, and the impact of design factors is discussed. Finally a conceptual model of interaction as an integrated process consisting of learning, effort, the cognitive dimension and the physical dimension is presented. Eight figures illustrating the components of interaction concepts are attached. (Contains 69 references.) (KRN)

INTERACTION STRATEGIES AND EMERGING TECHNOLOGIES

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ABSTRACT

While few question the importance of interaction for effective computer-supported learning, insufficient attention has been focused on the implications of contemporary research and theory for the design of such interactions. With the emergence of technologies of vastly expanded capabilities, the potential for interaction design continues to grow. What kinds of interactions should be cultivated? Are these strategies truly unique for specific technologies, or are they generalizable? How are different learning tasks accommodated in interaction strategies? Can guidelines be derived that reflect contemporary research and theory rather than specific transitional media? In this paper, several perspectives on interaction and computer technology are presented and critically analyzed, dimensions of interaction are examined, and a framework for the design of interaction strategies is presented.

INTERACTION STRATEGIES AND EMERGING TECHNOLOGIES

Few contemporary researchers, theorists, or practitioners question the importance of interaction in computer-aided learning. Interaction generally refers to purposeful, overt responses made during instruction and the consequences for lesson activities, content, or sequence. Interactions involve conditional, two-way exchanges between a learner and a learning system. Each exchange has the potential to alter subsequent transactions based on the intentions of the learner, the requirements of the learning system, or both.

Many views of have emerged regarding interaction strategies and emerging technologies. Computer scientists view interaction as a managed input-processing-output cycle. Traditional objectivists, on the other hand, describe this interchange in terms of stimulus-response-reinforcement ($S \text{-->} R \text{-->} S^R$) associations. Different, but related, views of interaction have also been espoused within the computer-based learning field. Bork (1982), for example, described three basic components: student response, computer analysis of the response, and the computer response to the input. Heinich, Molenda, and Russell (1989) stated that, for interactions to occur, learning systems must permit some physical activity, such as a typed response, which subsequently alters the sequence of presentation. A similar definition was proposed by Floyd (1982), who emphasized that conditional presentation sequences in interactive video must be controlled by user response. Generally, interactions comprise three generic activities: physical behaviors (action), processed responses (interpretation), and response-differentiated presentation (reaction).

Research on interaction has taken many forms. Prior to the widespread interest in computer-based instruction (CBI), researchers embedded questions to examine effects on related learning (see, for example, Carrier & Fautsch-Patridge, 1981; Friedman & Rickards, 1981;

Reynolds & Anderson, 1982). With the advent of CBI, the emphasis has been on embedding questions as well as exploiting the management potential of the computer through learner control and response-sensitive methods of branching (Park, 1984).

While there is widespread consensus as to the importance of interaction during learning, research has largely failed to generate reliable, empirically-referenced design strategies. Insufficient attention has been directed toward understanding the implications of contemporary research and theory. With the emergence of technologies of vastly expanded capabilities, interaction design potential has expanded dramatically. What kinds of interactions should be cultivated? Are these strategies truly unique for specific technologies, or are they generalizable? Can guidelines be derived, based upon existing research and theory, that emphasize more durable technological attributes? How are differences in learning tasks addressed in the design of interaction strategies?

In this paper, several perspectives on interaction are presented and critically analyzed, dimensions inherent in interaction are examined and a framework for the design of interaction strategies is presented.

TRADITIONAL PERSPECTIVES ON INTERACTION

Historical perspectives on interaction functions, purposes, and foundations have influenced strategy design considerably. Two perspectives will be considered: operational and functional.

An Operational Perspective

Operationally, interactions have focused on four steps: a physical response, feedback based on the response, a mental task, and symbols or codes used to convey information. The relationship among these steps is shown in Figure 1.

Insert Figure 1 About Here

Physical Response

The physical response is the cornerstone of traditional CBI programs. Lessons are designed to branch differentially based upon overt responses (typing, touching a screen) made by learners during instruction. More than any other feature, response-differentiated branching has distinguished computer-supported instruction from its non-interactive predecessors. Early applications, consequently, emphasized frequent responses to embedded questions, and differential branching based upon the accuracy of the responses.

Interaction strategies differ in the complexity of the physical responses. Fitts (1964) maintained that the time required to create associations between new and old information, and to develop appropriate responses by correcting movement errors, is contingent on the complexity of the skill: the more complex the skill, the more time required to strengthen associations. Holding (1989) noted that many complex responses, such as playing the violin, are continuous and involve substantial fine motor control. Other simple motor responses, such as throwing a ball, are more discrete physical tasks and involve significant gross motor control. Although both responses are physical, they are quite distinct in nature.

Complexity also refers to the number of simultaneous responses that must be elicited. In some cases, it may be desirable to elicit a series of simple responses which can be subsequently chained to form a complex physical response. Mané, Adams, and Donchin (1989), for example, maintain that in learning tasks involving a massive body of knowledge of graduated difficulty, a part-whole strategy best facilitated learning. In their experiment, subjects using a part-task strategy performed significantly better than those using adaptive strategies. Apparently, the breakdown enabled participants to respond to small pieces of a complex task, making them easier to assimilate. Wickens (1989), on the other hand, reported that adaptive training methods are often most appropriate for tasks involving complex physical responses. Adaptive methods simplify task complexity without altering the physical response itself. Over time, the complexity of the task is progressively increased though the response requirements remain essentially unchanged. Wickens suggested that for many complex learning tasks (tasks requiring more than one response), mastery is not only facilitated by adaptive training, but may actually be hindered by part-task training.

Early theorists (e.g., Skinner, 1938; 1960) suggested that physical responses should be congruent with the performance requirements of the instructional objectives. When learning to drive an automobile, for example, learners are required to press the brake pedal with their foot--the required physical response. However, in many cases the response does not adequately represent actual task requirements. In the driving example, participants might produce a nominal and largely unrelated physical response, such as pressing a button in order to apply the brakes. Whereas physical responses are required in each example, pressing the brake pedal better approximates actual task requirements, providing greater ecological validity to the interaction.

Response frequency is also a topic of considerable interest. Some have advocated frequent interactions both to control the amount of information to be addressed and to maintain active learner engagement. Bork (1985), for example, recommended that responses should be elicited every 15 to 20 seconds. Others have estimated frequency requirements in terms of the lesson's conceptual density, the individual's prior knowledge, and the cognitive load associated with the learning task (Hannafin, 1989). Generally, tasks that are conceptually dense or high in processing requirements require more frequent interactions than tasks of lesser density or lower cognitive load.

There is ample evidence that physical re-ponses, viewed traditionally as essential definitional components of interactions, are often misunderstood and unnecessary. Although interaction is the cornerstone of traditional views, there still exists a remarkable gap in our understanding of the role of complexity. It is clear that the nature of the response--its relationship to criterion tasks and complexity--affect greatly how, or if, learning will occur. At the same time, considerabie evidence exists suggesting that physical responses *per se* are not the most essential element of successful learning, and may even prove unnecessary or counterproductive.

Feedback

Traditionally, feedback and physical responses have been interdependent. Conventional notions of interaction require that a physical response be generated in order to differentiate subsequent feedback. Recently, however, the concept has been broadened. Adaptive feedback, for example, may be influenced by cumulative response history (Jonassen, 1988), unique individual historical data (Hannafin & Peck, 1988), or delays or failures to respond (Steinberg, 1991; Tennyson, Christensen, & Park, 1984). Contemporary views of feedback involve not simply strengthening specific associations, but providing strategic knowledge as well (Hannafin, Hannafin, & Dalton, in press).

The type of feedback also varies. Gagné (1985) noted that feedback facilitates performance when it is informative. At the most fundamental level, feedback might merely confirm that an acceptable response has been made. Other feedback strategies provide information that is conditionally relevant to the responses of individual learners. Dick and Carey (1990), for example, suggested that feedback should not only address correctness or incorrectness of responses, but also provide a rationale for correct or incorrect answers.

Computer technology has been lauded for its capacity to deliver individualized feedback (Roden, 1991). Schimmel (1988), for example, maintained that the greatest meaning can be extracted when the feedback follows immediately after the learner's response. Others (Charp, 1981; Dalton & Hannafin, 1984) have likewise emphasized the importance of immediate computer feedback to student responses. Presumably, contiguity between the response and the associated feedback improves the probability of strengthening desired associations.

Though initial views emphasized immediacy of feedback, subsequent research emphasized the importance of associated cognitive processing and the individual's response confidence (Kulhavy, 1977). Postponing feedback during interactions permits individuals to purge unimportant or poorly processed information from working memory facilitating the so-called delayed retention effect (Surber & Anderson, 1975). Brief delays may also minimize the influence of false-positive feedback resulting from chance guesses. Hannafin (1989), for example, noted that brief delays often facilitated learning by allowing subjects to self-correct or affirm responses through the induction of new knowledge.

There are predictable operational limits to the benefits of feedback. Schaffer and Hannafin (1986) maintained that performance increments associated with interactive video feedback reach a ceiling, after which little value is added. Learners reach a saturation point, where additional knowledge cannot be derived via increases in response-differentiated feedback alone. Typically, this point is encountered when the complexity of the learning task itself limits feedback's value, as in cases where individuals simply cannot process the additional information successfully due to a weak or deficient grasp of basic supporting concepts.

In summary, independent of the perspective taken, the value of feedback varies based upon learner, task, and prior experience factors. The probability of eliciting a desired response in the presence of a particular stimulus depends upon whether the individual's feedback history was punishing, reinforcing, or non-reinforcing (Klein, 1987): Feedback, like reinforcers, must be valued by the learner to be effective. Since information perceived as unimportant is unlikely to be processed very deeply (Hannafin & Hooper, 1993; Keller & Burkman, 1993), the perceived relevance of feedback is integral to effective interactions. The importance of feedback has not been seriously disputed; the nature of feedback, however, can vary widely.

Mental Task

Neither physical responses nor lesson-supplied feedback, traditionally defined, are always needed or desired. Research in observational learning, for example, has demonstrated that overt responses are often unnecessary for learning to occur (see, for example, Bandura, 1986). Much of what is learned by children, for example, is modeled vicariously with considerable mental processing but no associated physical responses. Presumably, learners perform certain cognitive operations that increase the memorability of knowledge. Some students might, for example, recall certain childhood events vividly in a sort of "flashbulb memory" (see, for example, Brown & Kulik, 1977; Neisser, 1982) whereas others might recall nothing under identical circumstances. Over time, physical responses may strengthen knowledge initially acquired vicariously, but it is often unessential to either initial acquisition or retention.

In certain cases, physical responses may actually inhibit learning. Baggett (1988) suggested that learning is not necessarily facilitated, and may occasionally be hindered, when physical responses are required. In her experiment, a series of treatments were administered providing differing levels of traditional (on-terminal) and hands-on (off-terminal) practice in building given objects. Some participants received only the basic information without either traditional or hands-on interaction, while others received combinations of on-terminal and/or hands-on practice. Baggett concluded that participants who received off-terminal practice were less efficient in constructing the objects than were those receiving only the on-terminal interaction. Additionally, no significant performance differences were observed between the non-interactive, passive response group and the interactive treatments. Apparently, increases in the physical response requirements actually hindered performance.

Interaction cannot be satisfactorily characterized strictly in terms of mediating stimuli and overt responses. Interactions must support the varied ways in which individuals make their knowledge meaningful. In order to be effective, interactions must emphasize mental, rather than solely physical, processes. While physical responses may help to elicit relevant mental activity, they in no way ensure them. Cognitive requirements, therefore, are of substantially greater significance than physical response requirements.

How, then, can mental resources be managed to promote needed cognitive processing? There are many views about the nature and dynamics of information processing. Most views assume limited capacity, making it essential that interactions aid the learner in selecting and processing relevant information in appropriate ways. A basic tenet is that a series of perceptually-driven transformations is made on environmental stimuli (Best, 1989). Stimuli are selectively processed, elaborated, and encoded within more inclusive schemata (Gagné, 1985). Meaningful learning, requires that learners integrate new with existing knowledge and restructure it accordingly.

Interaction strategies influence differentially the nature of processing. Several theorists [see, for example, Craik & Lockhart (1972); Hannafin & Rieber, 1989; Rundus (1977)] suggested that the greater the depth of processing, the greater the semantic analysis. Some interaction strategies (pressing a key when ready to continue) may require little or no semantic processing. The responses do not require the learner to select information purposefully, elaborate it richly, or encode knowledge in any form. Individuals, of their own volition, may do so, but the interaction fails to promote these processes. Other strategies (explaining the potential risks and rewards of a particular approach to a problem), on the other hand, require a great degree of deep semantic processing. Clearly, the cognitive requirements of interaction strategies can be vastly different.

Cognitive requirements also range along a continuum of complexity based upon the learners existing knowledge and the cognitive demands of the task. For novices, seemingly simple overt actions may have significant cognitive requirements (Solso, 1991). In physics, for example, predicting a value which best approximates the force of one object on another requires considerable estimation, computation, and comparison. The physical response (entering a numeric value) is quite modest, but the associated cognitive requirements are substantial. In other cases, however, relatively complex physical responses are required for tasks requiring only nominal cognitive processing. Some tasks, such as making a left-hand turn across oncoming traffic, are largely automated in seasoned driver and can be completed with little conscious effort.

Symbols and Codes

The attributes of the information presented to the learner (points, alphanumerics, frequencies, colors) can be thought of in terms of symbolic codes (Goodman, 1976; Salomon, 1976, 1979). Technologies vary widely in the codes they support. The successful use of codes during interactions is influenced by both their availability (technology dependent) and use (design dependent).

Interactions can be designed to vary both the number and type of symbols used to convey information. Information can be coded in verbal (meaning), imaginal (pictures), or both verbal and imaginal codes, and stored in either or both systems (Paivio, 1971). These representations retain dominant properties such as shape, size, and detail. Memory functions best when both semantic and imaginal representations can be cross-referenced. Interactions that support encoding of multiple, related representations provide complementary support during both encoding and retrieving.

Another difference among interaction strategies is the relationship between the external codes used during instruction and the internal codes used by learners. Salomon (1979) noted that learning is influenced by the compatibility between the external symbol systems employed during instruction and the internal representations generated by the learner. In some cases, interactions featuring visual symbols such as illustrations may help to organize a host of semantic concepts; in others, verbal information might be necessary to help individuals understand relationships coded visually.

The manipulability of codes can also influence learning. Symbol systems differ with regard to the coding elements utilized to convey information. Coding elements are "...elements which, when combined according to syntactic requirements, make up a symbol system" (Salomon, 1979, p. 132). One advantage of video, for instance, is that it can accentuate lesson content not readily identified by manipulating its formal features (zooms, pans, and rotations) (Pezdek & Hartman, 1983). Other technologies, such as digital video interactive (DVI®), compact disc interactive (CD-I®) and QuickTime™ offer substantial symbol manipulation capability. Since all information--textual, graphical, and video--exists in digital form, it can be altered dynamically. [This is true not only for the sequence of use, but for construction of the symbols themselves.] This provides significant design potential, but poses some unusual problems as well. Interactions can alter cognitive requirements by using selected symbols to supplant certain mental resources otherwise required to process information. Learners can then allocate their mental resources to other aspects of the lesson (Salomon, 1976). Conversely, symbol manipulations can cause competition for limited resources thereby increasing rather than reducing the cognitive demands of the task.

Considerable research has been reported on the influence of compatibility among presentation codes, suggesting that poorly selected codes can be detrimental to learning. Stroop (1936), in his classic study, found that subjects took significantly longer to read words referring to a given color ("blue") but written in a different color ("blue" written in red ink) than when the color and term were congruent. Decoding of verbal codes (words) was complicated by the incongruent presence of image codes (colors). More recently, using a color-word task, Cowan and Barron (1987) reported that subjects who listened to random color words performed poorer than those who listened to non-color words or music. Subjects who listened to nothing while identifying color words performed best, suggesting that learning is hampered when codes conflict.

Comparable findings have been reported for contextual learning tasks. Pictures have been found to support learning when they overlap with textual content, are congruent with evolving semantic meaning, and provide either redundant information or otherwise supplement textual content (Haring & Fry, 1989). Hannafin (1988) studied the effects of pictorial, oral-aural, and combined presentation codes on the learning and mislearning of explicitly depictable (concrete) versus difficult to depict (abstract) lesson content. Concrete concepts were learned comparably via either visual or verbal presentations, but pictures alone were ineffective in conveying abstract lesson concepts. Combinations of pictures and oral-aural, however, yielded both the greatest learning, and the fewest misunderstandings, of both concrete and abstract content.

The alignment of codes made available during interaction also affects the degree to which they can be effectively processed. How much information can be effectively assimilated, and through which modalities? Broadbent's (1958) early work in selection and attention [as well as the subsequent work of Cherry (1966), Neisser & Becklen (1975), and Treisman (1964)], emphasized limitations in the processes used to filter incoming stimulation. Learners, while capable of attending to more than one message in the same modality to a nominal degree, generally focus on one message to the virtual exclusion of others. For example, during flight instruction requiring simultaneous attention to ground control instructions and the comments of an in-flight instructor, only one of the sources will likely be attended to until one of the processes becomes automated. Complimentary use of processing resources (visual, auditory, tactile, olfactory), however, tends to strengthen rather than hamper processing efforts. Interactions featuring tactile stimulation and complimentary information derived from graphical displays and voice, such as provided in cockpit simulators, can provide a rich variety of codes to support learning.

Research suggests that the codes used during interaction can either facilitate or hinder learning. Learning will be facilitated to the extent that the information supports, and does not interfere with, appropriate processing. When very abstract codes or a poor combination of codes have been chosen, the ability to process the information decreases.

A Functional Perspective

Functional views emphasize how interaction is used, and the varied roles it plays in learning systems. Hannafin (1989) identified five functions: supporting lesson pacing, providing the opportunity to elaborate, confirming the accuracy of responses, navigating within or across lessons or lesson segments, and supporting inquiries from students.

Pacing

Pacing refers to the metering of information as learners move through lessons and activities. Pacing is more often related to lesson flow than to the achievement of instructional objectives. Although metacognitive judgements are presumably made by individuals, both the nature of the physical response and the associated cognitive requirements tend to be minimal.

Simple pacing interactions often take the form of instructions to "press any key to continue." It serves to meter the rate of information flow according to individual factors, allowing the student to re-read, study, or release information from view. However, pacing interactions may also affect the start, stop, and suspension of ongoing information flow, as individuals seek to speed-up, slow-down, or terminate lesson activities.

Elaboration

Another function of interaction is to elaborate the information presented. Elaboration strategies may or may not not require physical responses, depending on the nature of the task and the biases of the designers. Learners might, for example, be encouraged to either consider mentally how a new concept shares similarities with previously learned concepts, type a brief response that relates lesson information to individual experiences, or both. Where no physical response is required, individuals may be prompted to focus attention on specific issues and generate meaningful relationships that are consistent with the learning task.

With emerging technologies, the range of elaboration options is quite diverse. Elaborations might be accomplished via embedded notetaking tools which permit the individual to write ideas and thoughts during the lesson. Interactions also permit access to on-line utilities through which the student can obtain additional related information. Finally, annotation tools might be provided which permit the individual to notate lessons.

Confirmation

A third function of interaction is to confirm the accuracy of student responses to problems posed during the lesson. In many cases, students respond to textual questions in the form of typing a single keystroke or short answer. The response is subsequently evaluated against established criteria, and the lesson proceeds accordingly.

However, confirmation can also be provided during real-time, natural image simulations such as emergency room simulations [see Harless (1986) for a description of the simulation, *The Case of Frank Hall*]. Participants recommend test and intervention procedures and examine their impact. Alternatively, students might be expected to respond in "ideal" ways as in expert-referenced problem solving. The interaction provides confirmation of the accuracy (or desirability) of student knowledge.

Navigation

Interactions also support navigation. Navigational options are often provided either explicitly presented or implicitly via menus. Lessons might be explicitly structured into sections (introduction, rules, examples) or supporting activities (glossaries, help) which provide on-demand access to available activities. In contrast, control can also be accomplished by selecting and touching a given area of a monitor, where navigation logic is implicitly defined (touching a part of the body).

Hypertext, non-sequential access to educational resources (Gall & Hannafin, 1993; Jonassen, 1988), poses unique interaction problems. Hypertext may be structured in a more or less explicit manner providing fixed control, where links are structured selectively based upon particular linking paradigms (hierarchies, nodes) to connect defined elements of a lesson. or dynamically providing theoretically unlimited options. Hypertext links can also be defined dynamically by connecting the lesson elements uniquely selected by individual. [See, for example, Yankelovich, Haan, Meyrowitz, & Drucker (1988) for a description of *Intermedia.*].

Inquiry

Inquiry interactions permit the user to address, directly, the contents of a lesson, system, or knowledge base. In some instances, the inquiry might be related to performance information, such as current test scores of a lesson already completed. Hc ever, in sophisticated circumstances, the individual might engage in a dialog with the system itself, such as a medical expert system designed to assist in diagnosis or a database designed to locate relevant legal precedents. Through inquiry, the user can trace the etiology of a disease or identify important legal foundations. Typically, the system embeds structures to access available data; the individual interacts using the established methods and parameters.

An Integrated Perspective

Operational and functional perspectives reflect different, but complimentary, aspects of interaction. Yet, neither addresses satisfactorily the complexity of interaction strategy design. Operational perspectives offer global information related to the elements of interactions, but fail to reveal how the response, the mental task, feedback, and the symbols should be combined to facilitate learning. Functional perspectives provide ways to conceptualize interactions in relation to their role within the lesson, but do little to account for the cognitive demands attendant to their use.

Clearly, different forms of interaction exist, each of which varies not only according to the function of the interaction but to the nature of the learning task. Each has different cognitive requirements, employs varied response formats and feedback, and uses diverse combinations of symbols and codes. The manner in which the operational elements are implemented varies dramatically both within and across interaction functions.

At the center of this problem may be inadequate definition. Traditional definitions (i.e., physical response, feedback, mental response) emphasize observable elements, but fail to reflect the presumed cognitive consequences. Using traditional definitions, all elements may be provided yet yield none of the desired cognition Alternatively, few elements might be provided yet yield exceptional learning. Working definitions of interaction, therefore, must focus on cognitive requirements and consequences.

From an integrated perspective, interaction is an educational process designed to assist learners in acquiring or restructuring knowledge by mediating an investment of effort and the allocation of cognitive resources. This is acheived through exposure to one ore more stimuli. An important aspect of this definition is that a physical response, by itself, is neither a necessary nor sufficient condition for interaction. The critical factors are intentionality in the investment of effort and the associated acquisition and restructuring of knowledge (processing). Still, while interaction necessarily involves a cognitive rather than a physical response, the importance of physical responses cannot be easily discounted. Learners are required to invest effort differentially, so the degree to which physical responses engender requisite cognitive processing is critical.

Dimensions of Interaction

Interaction processes can be concep: .alized as ha\ing multiple, interactive dimensions. Both the response requirements and the methods employed influence the effectiveness of interaction strategies. Response requirements focus on internal (cognitive) and external (physical) responses of learners, while design factors focus on the quality and quantity of the interaction processes. The relationships among these dimensions are shown in Table 1.

Insert Table 1 About Here

Response Requirements

Cognitive. Cognitive requirements emphasize processing and understanding (Hooper & Hannafin, 1991). This dimension parallels certain aspects of Salomon's concept of Amount of Invested Mental Effort (AIME). Salomon (1981; 1983; 1984) defined AIME as the number of non-automatic elaborations applied to a unit of material. In the present context, mental effort refers to interaction-induced cognitive activity designed to process lesson information. In general, increases in purposeful mental effort should improve learning while decreases should hamper learning in proportion to the effort invested. These relationships are shown in Table 2.

Insert Table 2 About Here

However, simply increasing the amount of purposeful processing activity does not ensure successful learning. Norman and Bobrow (1975) distinguished between data-limited and resource-limited processes. In the present context, data-limited processing, the investment of additional processing resources, cannot, by itself, improve learning. Data limitations derive from both external and internal sources. Internal data-limited processes may reflect an individual's knowledge deficiencies. For example, despite sound external organization, lesson content may be too complex given the learner's existing knowledge: The learner may simply lack the requisite knowledge or skills. Additional effort will not likely improve learning, and may cause considerable frustration. External data limitations are reflected in unintelligible stimuli or deficient organization of to-be-learned content. In either case, the extensive data limitations render additional effort unproductive.

Resource-limited processes, on the other hand, are often more amenable to improvement through additional effort. Resource-limited processes are influenced by the ability of the learner to invoke (internal), or the learning system to supply (external), activities that aid the learner in processing lesson content. Poorly organized or presented lessons, wherein important information is obscured, can be overcome to the extent internal or external resources can be invoked. In some cases, individuals may invoke content-independent metacognitive strategies, such as spontaneously-generated elaborations, to encode essential lesson information (Osman & Hannafin, 1992). In other cases, the system itself may prompt the individual to generate mental images based upon the concepts presented in the lesson.

Resource-limited process improve performance to the extent that strategies are appropriate to the processing requirements and do not compete for the same cognitive resources. Learning is stimulated when individuals both have the required resources *and* invest the effort necessary to allocate their resources appropriately. For interaction purposes, the merging of the mental effort and multiple resource perspectives yield four possible scenarios. These options are summarized in Table 3.

Insert Table 3 About Here

In the first scenario, the student has neither access to "clean" data, the resources available to process data, nor invests mental effort in the task. This is evident in many disenfranchised adolescents who demonstrate significant achievement deficits and negative attitudes towards learning. Students lack not only the basic data (knowledge) required to process lesson content, but are also disinclined to invest the mental effort required overcome the deficits. The data are sufficiently "noisy" as to render them uninterpretable, and learners possess neither the willingness nor the ability to understand them. Clearly, the potential for interaction to support learning is weakest under such circumstances.

Next, the student neither possesses, nor has available, the needed resources but attempts to invest mental effort. This situation arises with learners who invest considerable energy in attempting to understand, but fail to comprehend due to limitations in either the enabling knowledge or the strategies needed to process the information. When learners attempt to understand a severely faulty message, such as a distorted overseas radio transmission, they might invest considerable effort in an attempt to interpret the poor data. Unless the message retains sufficient intelligibility, it is uninterpretable rendering the additional effort of comparatively little value.

The third scenario results when students possess the required resources but do not invest the mental effort. This is typically seen among bright, underachieving students. They often possess both significant related knowledge and complimentary learning strategies, but fail to invest the effort required to comprehend. Learning of otherwise intelligible information would not be expected since, while the data are appropriately organized, the willingness to engage the material is lacking.

Finally, learners possess the needed resources and invest mental effort appropriately. This i' the ideal scenario, and one which interactions are most likely to promote engagement successfully. Lesson data are well-organized, and learners engage lesson content appropriately using both their previous knowledge and metacognitive strategies.

In summary, the extent to which interactions support appropriate processing is influenced by both the nature of resources appropriately applied and the amount of invested mental effort. Individuals may invest considerable mental effort, but if the interactions induce the investment of resources in unrelated data or processes, learning will be ineffective. Further, interactions might demand resources that are unavailable or inadvertently overtax those that are available. Some information will be processed ineffectively while other information might fail to be processed at all. Finally, interactions may misdirect the allocation of cognitive resources to processes that, while related to the desired outcomes, fail to invoke mental effort appropriately.

Physical. Physical responses prove beneficial when they assist in directing attention, provide complementary stimulation or information, supplement existing lesson information and meter its flow, illustrate and clarify lesson concepts, and approximate the sensory aspects of a task. Not all physical responses, however, meet these criteria. Individuals routinely act in observable, physical ways that do little to stimulate, clarify, or strengthen understanding. Responses are often routinized and engender little cognitive activity such as mindlessly pressing keys to advance to the next lesson frame. While some cognitive activity is involved, both the physical responses and associated cognition are largely automatic in nature and require little or no investment of mental effort. For physical responses to be integral to the success of the interaction, they must influence processing activities and effort in meaningful ways.

Like cognitive activities, physical responses can be either purposeful or non-purposeful. Purposeful responses reflect the decision to purposefully examine the causes and consequences of the response (cf Hannafin, Hannafin, & Dalton, in press). A typed response to an embedded question, for example, generally indicates awareness and intentionality by the learner. It is the product of active processing and responding. Non-purposeful responses represent little or no active learner processing. In some cases, they are largely unconscious, "mindless" responses.

The relationship between the physical response and mental effort is bi-directional. Mental effort may be the impetus for, the product of, or both the impetus for and product of physical responses. For instance, upon observing that a simulated airplane will crash if its glide path is not corrected, learners must adjust the approach angle of the aircraft. Mental effort is invoked as a reaction to changes in immediate circumstances, which in turn provide the impetus for purposeful physical responses. In contrast, physical responses often cause the changes observed in circumstances. An individual might unintentionally break a flask containing highly corrosive acid, requiring the rapid development and implementation of a plan to control the potential damage. Whether intentional or unintentional, the response may supply the impetus for subsequent processing activities. The physical response, in this example unintentional, triggered relevant cognitive activities.

As noted previously, physical responses do not always support learning (Baggett, 1988). From multiple resource and mental effort perspectives, physical responses hamper learning when they compete for resources required to successfully process knowledge (Gopher, Weil, & Siegel, 1989; Wickens, 1992). Important data may go undetected due to response requirements that misdirect attention, such as in responses that focus on unimportant information or concepts or interrupt continuity. The physical response may significantly mismatch actual performance requirements, such as requiring complex typing when simple responses are appropriate. Cognitive resources may become overtaxed by excessive processing demands associated with the physical response itself as in the case of complex, but non-essential response procedures.

Finally, while physical responses may initially interfere with learning, they can increase in effectiveness through usage. As the physical response becomes automated, competition for resources is reduced thereby freeing processing resources. Responses to complex computer simulations may require considerable cognitive resources initially, but as individuals become increasingly familiar, the cognitive resource requirements decrease and the productive value of the response increases.

Design Factors

Quality. Quality refers to the richness and appropriateness with which resources are invested during an interaction, and the role of both cognitive and physical responses in improving processing activities. It emphasizes the activation of cognitive processes most beneficial to the individual.

Quality can also be defined in terms of value. High-quality interactions ensure that relevant cognitive processes will be activated, resulting in learning that is accurate, usable, flexible, transferable, and durable. High-quality interactions heighten cognitive engagement causing the learner to deepen the processing of knowledge, associate new with existing knowledge, and construct meaning accordingly. For example, high-quality interactions related to the concept of gravity might provide learners the opportunity to examine the influence of planet attributes. The influence of variables such as mass and density on the weight of objects can be examined, allowing individuals to generate, test, and revise hypotheses on the relationships among them. The interaction supports the acquisition of not only simple rules, but the conditional and interactive relationships among concepts as well.

Low-quality interactions promote cognitive activity that is insufficient, ineffective, inefficient, inappropriate, or counterproductive. The interaction fails to engage the learner cognitively in appropriate processes. Often the interaction causes the individual to attend to unimportant or irrelevant information. Perhaps the interaction activities are not well suited to the types of processing desired, causing the individual to misallocate cognitive resources. In either case, the interaction strategy failed to stimulate high-quality processing.

Quality can be further differentiated according to different perspectives: designer versus learner. Value may be assigned by the designer based upon external factors such as the presence of multiple, complimentary coding mechanisms or the integration of apparently related concepts. Alternatively, quality is interpreted by the individual based upon internal factors such as the perceived relevance of the interaction. To the extent that the criteria of both internal and external sources are addressed, interaction quality should be high.

Often, however, the quality judgements of designers and learners are inconsistent and at cross-purposes. A designer's view of quality is typically based upon beliefs about stimulus attributes, the apparent connectedness among lesson concepts, the presumed importance of lesson concepts, and so on. Quality judgments, in effect, are based upon external beliefs of what is relevant to learners. Learners, in contrast, supply a unique, personal view of quality. Quality is perceived individually according to its relevance to unique knowledge, needs, and experience, as well as its practical significance and personal implications.

Two qualitative variables influence the processing of knowledge resulting from physical a response: the complexity of the response and the specificity of the resulting feedback. As noted previously, complex responses initially require significant cognitive resources in order to simply meet the response requirement. Considerable mental, and occasionally physical, effort must be expended in order to automate basic physical and cognitive responses. Specificity of feedback refers not solely to the literal explicitness of information, but to its relevance to learning goals. To the extent that information is unambiguous and well-aligned with such goals, learning will generally be facilitated; to the extent feedback provides additional information which obscures or otherwise masks meaning, learning will be inhibited.

Finally, the amount, appropriateness, and interpretability of feedback are associated with interaction quality. Too much information will likely overtax the individual's cognitive resources, rendering processing efforts of little value. [Again, as familiarity with to-be-learned concepts increases, the amount of information that can be processed effectively generally increases; as familiarity decreases, the amount decreases.] Inappropriate, or extraneous, data causes the individual to allocate resources to concepts that are unimportant often complicating the task of selecting important from unimportant information. Unclear, uninterpretable, or "noisy" data promote inefficient use of resources, and tend to require extensive effort with comparatively modest payoffs.

Quantity. Quantitative factors refer to how much physical (frequency, demands, timing, and density of responses) and cognitive (number of elaborations, covert repetitions, amount of processing) responding is fostered during interaction. Quantitative views emphasize factors such as frequency, motor requirements, and temporal requirements and their corresponding influence on mental effort and cognitive processing. Generally, as the quantity of task-appropriate interactions increases, the number of opportunities for producing physical responses, investing mental effort, and utilizing processing resources increases.

As noted previously, quantitative views have dominated traditional views of interaction. It is conceivable that increases in quantity will elevate mental effort and alter the investment of cognitive resources, but the nature of the processing activities may not support learning. Depending on the quality of the interaction, learning may or may not be facilitated. If the quality is poor, learning will not increase, and will often decrease as the quantity of interactions increases. Responses may be mismatched with the learning task, the physical or cognitive demands may overtax the individual's processing capacity, the responses may compete for the same resources, or the activities may promote the use of multiple, non-complementary, processing resources. The effort may be misdirected, and the resources poorly allocated. If the quality is good (induced appropriate investment of mental effort and allocation of cognitive resources), learning should increase as the quantity of interaction increases.

It is useful to consider quantit' from multiple resource and mental effort perspectives. If the interaction invokes identical mental processes, then increases in quantity provide additional directed processing related to the task. Increases in quantity may improve the automaticity of the learned skill. To the extent that lesson information has not been processed completely, resources could continue to be allocated to the task. However, as learners become increasingly proficient, less "new" information exists to be processed via interactions. If, during subsequent interactions, learners continue to invest effort and invoke resources as initially done, effort and resources would be ineffectively utilized. Fewer resources would be available to deepen understanding, resulting in inefficient interactions. Benefits would continue to diminish until either new information were presented or until mental effort and cognitive resources were focused on different tasks.

If the interaction invokes cognitive processes that are non-repetitive but complementary (i.e., different mental processes employed for various aspects of the task), on the other hand, then interaction quantity functions to develop rich knowledge structures. Effort is sustained by the diversity of the activity, and resource-based processing mechanisms can be utilized accordingly. Lesson content and concepts are processed in complementary ways to provide multiple perspectives.

If, however, interactions fail to provide sufficient processing guidance or exceed the individual's processing needs, then learning will be hampered. Mental effort may be sufficient, but resource limitations will diminish the effectiveness of the interaction. When provided with too little interaction, individuals often fail to master or automate knowledge and skills. The production value of the resulting knowledge is inherently limited.

In certain cases, too little information must be processed simultaneously, while in others too much information must be processed. When too little information is to be processed, the task loses meaning. The increments are too small to promote meaningful integration, mental effort is reduced, and cognitive processes are either not actively engaged or are engaged in processing information other than from the task. For example, interactions emphasizing exceedingly small steps tend to decontextualize knowledge often making the isolated data appear unimportant and obscuring part-whole relationships. Individuals become bored, connections among related knowledge obscured, and overly segmented encoding is cultivated. When too much information is to be processed, or when the activities stimulate non-complementary use of cognitive resources, cognitive capacity becomes overtaxed. It becomes difficult to identify which relationships the interactions are designed to strengthen, and the responses generate more confusion than confirmation. Working memory becomes overloaded as a consequence of excessive data demands or cognitive resource requirements, rendering the individual's processing resources ineffective.

The nature of the codes employed during interaction can influence both the cognitive resource requirements and the mental effort necessary to process information. As the correspondence between the codes used during presentation and the internal codes employed by learners increases, less effort is required to process the data. This is consistent with Salomon's view that learning improves when the codes used during the interaction and those employed by the subject are complementary.

In contrast, code usage can also hinder learning by presenting competing symbols, such as reading about a city's history while simultaneously listening to taped explanations about cultural events. Interactions of this nature would likely be more effective if the messages were related (historical background and historical landmarks), and the symbol systems were either congruent (reading about the city's history while viewing pictures of the city's landmarks) or complementary (viewing pictures of historical landmarks while listening to an account of the city's history).

Clearly, the issue of "how much" is integral to interaction strategy design. However, quantity per se provides a limited and often misleading perspective. Simply increasing the frequency or physical demands of a response does little to promote learning. Instead, the effects of quantity are jointly mediated by cognitive and physical response considerations, and by the qualitative aspects of the response.

INTERACTION AS AN INTEGRATED PROCESS: A CONCEPTUAL MODEL

The model is rooted in eight assumptions about interaction as an integrated process.

Interaction processes are influenced by both external and internal factors. Interaction effectiveness is mediated in part by the clarity of the codes used in the medium, and in part by cognitive resources available to the learners. "Noisy" and unclear messages increase the cognitive load associated with interpreting meaning, thereby increasing the effort required to simply decode incoming data. For example, presentations that are poorly organized or provide unclear feedback increase the load attributed to external aspects of the interaction process. Individuals, on the other hand, may possess little requisite prior knowledge rendering interactions ineffective. Clearly, both external and internal aspects require careful consideration in designing interactions.

Learning from interactions requires the allocation of physical and cognitive resources. Actions such as pressing buttons or "pointing and clicking" electronic mice should not be expected to improve learning if individuals fail to attend to relevant aspects of the interaction. The mere production of a response, by itself, may or may not reflect of thoughtful processing. Likewise, important consequences of the response may go largely unattended rendering interactions of little value. For interactions to be effective, they must cause the individual to attend to relevant dimensions of the process prior to, during, and/or upon completion of a response. The individual must allocate needed cognitive resources to ensure that the data are properly identified, organized, and integrated.

Individuals possess limited cognitive resources with which to process data during interactions. Limitations refer not only to the availability of processing resources, but also to the number of resources that can be simultaneously allocated. Computers, for example, can display data far more rapidly than can be processed by humans suggesting that resources can be quickly overtaxed. As resources become increasingly saturated during interactions, information becomes more difficult to detect and process.

The effectiveness of interactions increases as competition for the same resources decreases, and decreases as competition for the same resources increases. Considerable research exists demonstrating the problems associated with competition for resources. Problems tend to be most pronounced when processes compete for the same cognitive resource. The task for novice pilots, for example, is often unduly complicated by the need to simultaneously (and with great mental effort) control the aircraft, listen to a flight instructor, and receive traffic control directives from air traffic controllers. Similar experiences are common among aspiring automobile drivers. Both novice pilots and drivers experience considerable frustration and anxiety when confronted with simultaneous data, occasionally with tragic consequences. The tasks compete for the same cognitive resources, forcing attention to one at the virtual exclusion of the others. Ideally, interaction processes support the activation of complementary resources.

The efficiency of interactions increases as the proportion of automated vs. conscious cognitive processes increases, and decreases as the proportion decreases. Automated processes occur without intention, require no conscious effort, and consume few or no cognitive resources (Posner & Snyder, 1975). This suggests that as interactions utilize more automated processes, available resources can be directed to the non-automated aspects of the interaction. Conversely, when not automated, degradations in performance will likely occur in all tasks, since only one of the simultaneous messages will be effectively processed. In the previous example, novice pilots and drivers will continue to experience difficulty until one or more of the processes becomes automated, allowing the allocation of effort to one task without performance decrements in the other.

There is an optimal efficiency level for intentional learning: As effort increases and appropriate resources are available, the efficiency of learning increases. While considerable incidental learning insights can be derived through interaction, pragmatic limits exist regarding how much interaction is reasonable. Efficient interactions help learners to allocate available resources to process information while avoiding undue repetition and effort. Inefficient interactions, while ultimately attaining the intended outcomes, often misdirect effort and require greater time and effort to attain intended performance levels. Usually, intentional learning is specified in the form of an instructional or performance objective which isolates both the lesson content as well as conditions and standards for successful learning. The issue, then, focuses on the efficiency of effort required to reach a specified standard. As effort is properly allocated and the requisite resources are available, efficiency increases; as effort is misdirected, resources misapplied, or needed resources are unavailable, the efficiency of intended learning declines.

While interaction processes influence both intended and incidental learning, one type of learning may improve at the expense of the other. The effectiveness of interaction processes for intentional learning has been well documented in studies of embedded questions--especially for the learning of verbal information and low-level intellectual skills (see, for example, Tudor & Bostow, 1991; Van der Linden & Assink, 1990; Weir, 1989). Given clearly defined learning outcomes, strategies can be readily developed to ensure the learning of such content. Likewise, interactions of a less explicit nature may improve overall understanding, but result in poorer learning of related lesson detail. Ideally, interaction processes should reflect a balance between the learning of explicitly identified concepts and the contexts within which they acquire meaning. Integrative interactions, where supporting details are anchored within meaningful lesson contexts, promote both intentional and incidental learning (Hannafin & Rieber, 1989).

The effectiveness of interaction processes varies as a function of the quality and quantity of both cognitive and physical resources. Although physical responses are neither necessary nor sufficient for learning to occur, they can influence the manner in which mental effort is allocated. In some cases, the physical response requirements are significant while in others, the requirements are nominal. The effectiveness of any interaction is a function of the correspondence between the physical and cognitive aspects of the strategy and the extent to which the quantity and quality of the response relates to the learning task. Designers may underestimate effort requirements or the amount of responding required to induce relevant cognitive processes, resulting in insufficient processing; likewise, the requirements can be overestimated causing unnecessarily repetitious processes. The processing activities may emphasize aspects that are unessential or unnecessary, resulting in misdirected mental effort (Salomon & Perkins, 1989). The physical and cognitive effort requirements of the task must be complementary in nature.

Overview

The model, shown in Figure 2, consists of four components: learning, effort, the cognitive dimension, and the physical dimension. The resource and effort requirements for a given interaction, the proportion of net learning accounted for by the vector components, and the balance among cognitive, physical, and effort factors associated with intentional and incidental learning can be represented. In addition, profiles of both the theoretical requirements associated with interactions as well as the observed interaction processes can be represented.

Insert Figure 2 about here

The model contains three vectors which share a common origin (O). Two of the vectors, which represent the physical (P) and cognitive (C) resource requirements, correspond to the x and y axes. The length of the vectors varies based upon the processing resources demanded during the interaction: As more resources are required, the length of the corresponding vector increases; as fewer resources are required, the length decreases.

The effort vector (E), which represents the effort required to learn the intended knowledge or skill, varies according to the resource requirements of the interaction and the nature of the learning task. The length of E varies according to task demands: The more demanding the learning task and the greater the resources required, the greater the length. As effort requirements become more cognitive in nature, E approaches C; as effort requirements become more physical in nature, E approaches P. Independent of the allocation of cognitive and physical resources, intended learning cannot be attained unless the effort requirements for intended learning have been met. However, learning is not merely mediated by effort alone; intentional, as well as incidental, learning is an interactive function of the investment of cognitive resources, physical resources, and effort.

The shaded area in Figure 2 represents the intentional learning theoretically associated with the interaction. The overall intended learning attributed to a given interaction is the area formed by connecting the origin and the endpoints of vectors *C* and *P*. By referencing the areas formed by *O* and the *E*, *C* and *P* vectors, the relative contribution of cognitive and physical components to overall learning can be estimated. Learning attributed to physical resources is defined as the area formed by connecting *O* and the endpoints of *E* and *C*. Learning associated with the cognitive aspects of the interaction is defined as the area formed by connecting *O* and the endpoints of *E* and *P*.

Both quantitative and qualitative aspects of the interaction also affect its effectiveness. The quantitative and qualitative aspects of interactions are often reciprocal in nature: Qualitative requirements tend to increase as the quantity of effort decreases, and vice versa. This implies that, during well-managed instruction, the cognitive demands of an interaction can be reduced by increasing the frequency of relevant responses; conversely, cognitive demands tend to increase as the frequency of interactions decreases. Increases in quantity alone, however, are unlikely to improve learning without corresponding increases in the quality of the effort and the investment of processing resources.

Increases in quantity tend to increase the lengths of the *C* and *P* vectors. In well-managed interactions, quality improves as the cognitive load is systematically distributed over more frequent, but less demanding interactions. New content can be introduced during successive interactions, metering the processing requirements across interactions while managing the cognitive demands of each. In other cases, however, the quality of effort may deteriorate with increases in quantity. Insufficient additional data are provided during subsequent interactions, resulting in an increase in quantity of effort but with little or no qualitative payoffs.

The complexity of interaction can also be progressively increased without causing either competition for similar resources or overtaxing of complementary resources. The quantity of effort, for example, may remain relatively constant while qualitative requirements are progressively expanded. Consider, for example, the interaction requirements of learning multiplication skills. Individuals initially learning to multiply typically begin with two single-digit numbers whose product is less than 10 (e.g., 2x3, 1x9, 0x4). Once appropriate responses are reliably obtained, more difficult multiplication problems are posed thereby increasing the qualitative aspects of the task while maintaining similar quantitative requirements (e.g., 5x5, 7x3, 8x9). After several appropriate responses have been entered, progressively more difficult multiplication problems can be posed.

Theoretical Interaction Profiles

Balanced Resource Requirements. The task represented in Figure 2 requires identical quantity and quality of physical and cognitive resources, as well as optimally efficient effort for intentional learning. Vectors *C* and *P* represent the minimum resources required to process data effectively during a given interaction. Under such circumstances, the ends of each of the three vectors form a straight line suggesting that the amount of effort and the distribution of physical and cognitive resources is designed for optimal efficiency with respect to intended learning.

Greater Cognitive Resource Requirements. In contrast, Figure 3 represents a learning task where the cognitive requirements are substantially greater than the physical requirements. This learning task may require a high school student to select and test a hypothesis that best accounts for the influence of forces of unequal magnitude and direction on the flight of a baseball in three-dimensional space. The task has very nominal physical requirements, apart from selecting among a given set of options, but the cognitive requirements are substantial. Considerable cognitive restructuring must occur, tentative predictions must be generated, the results must be observed and integrated within a theory in action, and the process must be repeated until a satisfactory solution has been found. Vector C is substantially longer than P, depicting greater cognitive than physical requirements of the interaction. Again, the endpoint of vector E coincides with the line connecting the endpoints of P and C suggesting optimal intended learning efficiency.

Greater Physical Resource Requirements. Figure 4 represents a task for which both the resource requirements and the learning contribution is greater for physical than cognitive. The figure illustrates the requirements involved in learning to ride a unicycle, wherein the physical aspects of the interaction far outweigh the cognitive components. Effort is allocated to mount the cycle, pedal without falling off, maintain balance, and steer the cycle. These rely heavily on the allocation of physical resources and the ensuing feedback, but to a lesser extent on cognitive resources. Again, the alignment of the effort vector implies optimal efficiency.

Insert Figures 3 & 4 about here

Observed Interaction Profiles

Thus far, we have focused on the theoretical aspects of interaction processes. The model can also be used to compare theoretical with actual interaction processes. Each vector has two distinct points represented by subscripts: One represents the theoretical (t) and the other the actual (a) resource or effort requirements. These points are identified in the following manner: C_t and

C_a for the theoretical and actual cognitive resource requirements, P_t and P_a for theoretical and actual physical resource requirements, and E_t and E_a for theoretical and actual effort requirements. The connections defining learning areas are represented in the same manner as described previously: Actual learning attributed to a given interaction is the area formed by connecting the origin with the endpoints of vectors C_a and P_a. In this manner, the learning differences resulting from actual interaction strategies can be represented conceptually, and the relative impact of the variations can be isolated with reference to both intentional (planned) and potential incidental learning.

Theoretical vs. Actual Effects. Figure 5 illustrates the effect of excessively high allocations of physical resources compared with the theoretical requirements of the intended learning task. Effort, in this example, is invested at levels consistent with the intentional learning task, while a corresponding reduction in the allocation of needed cognitive resources occurs. Intentional learning is reduced considerably due to the over-allocation of physical resources and the associated under-allocation of cognitive resources. Only partial learning of the intended content (the area bounded by the origin, P_t , E_a, and C_a), while a significant portion of intended learning was not addressed (the area bounded by E_t , C_a, and C_t).

Differential Investment of Effort. A special case arises with respect to effort. Intentional learning can only occur to the extent that the specified minimum effort required (E_t) has been actually invested. Stated differently, actual effort investment must be greater than, or equal to, the theoretical effort requirements for intentional learning to occur completely (i.e., $E_a \geq E_t$). Increases in either cognitive or physical resources, or both, cannot compensate for shortcomings in actual effort (E_a). This phenomenon is illustrated in Figure 6. Despite unlimited increases in C_a and P_a, intentional learning cannot occur completely.

Insert Figures 5 & 6 about here

Incidental Learning. Within the model, incidental learning is defined as a *potential* by-product of increased (or misdirected) effort, physical resources, or cognitive resources. Incidental learning represents the effects of interaction processes in addition to, or in lieu of, intentional learning. Productive incidental learning occurs to the extent that effort and resources investments increase the quality or meaningfulness of related knowledge. The mere additional allocation of effort, or the invoking of additional cognitive or physical resources, is unlikely to engender significant incidental learning.

Incidental learning can occur in addition to, or at the expense of, intentional learning. The relative cost of incidental learning is a function of the tradeoffs made for intentional learning and the nature of the effort or processing required to attain it. If intentional learning tradeoffs are made, the interaction is considered inefficient since it failed to yield its intended effect. If, however, intentional learning tradeoffs are not made, then the value of incidental learning increases as the efficient use of resources and effort increases.

As shown in Figure 7a, incidental learning can result from increases in effort independent of cognitive or physical resource requirements. In this case, the learner invested substantially greater effort than required for intentional learning, but the resource requirements remained essentially unchanged. The individual may have been provided more practice problems than necessary for given knowledge, resulting in the learning of both intentional as well as incidental information. Figure 7b reflects an incidental learning gain associated with an increased investment of cognitive resources. This might take the form of inducing mental elaborations of the content using existing, related knowledge. In this case, the effort required for the learning task remained constant, but additional cognitive resources were allocated which yielded incidental learning gains.

Insert Figures 7a and 7b about here

In contrast, incidental learning gains can be associated with losses of intentional learning. Figure 5, for example, depicts a differential investment of resources, with the proper effort investment, but greater physical resources and fewer cognitive resources actually expended. This might be evident in simulations where the complexity of the physical task using the computer (complex keystroke sequences) distracts from cognitive processing activities. The actual investment of resources failed to match the theoretical resource requirements, yielding some incidental learning potential, but a corresponding reduction in intentional learning. In Figure 6, the learner's actual effort investment was less than the theoretical ideal, while the actual investment of both physical and cognitive resources exceeded the optimization estimates for intentional learning. Both kinds of learning occur, but there was a distinct loss of intentional learning.

Implications and Conclusions

The proposed model offers a method in the design of interaction processes which both extends conventional approaches and integrates cognitive concepts related to the allocation of resources. The model provides not only a method for accommodating the operational and functional aspects of lesson execution, but a conceptual process through which interaction requirements can be estimated and observed outcomes compared.

Several implications of the integrated model can be cited. First, by recognizing interaction as a mental process rather than a discrete action, the role of mediating these processes can be accounted for as a product of planned design versus a tacit assumption stemming from physical response. Few designers dispute the important of processes, but still fewer reflect the importance of such processes in meaningful ways. The tendency to characterize interaction processes as mere physical tasks involving the production of an overt response is not only insufficient, but potentially misleading as well.

Next, attention to the roles and limitations of processing resources provides necessary conceptual guidance to interaction design. The tendency to view interaction design as predominantly external manipulations has blinded designers to the more important internal processes that should precede, be invoked during, and follow responses. Greater awareness of the importance of processing resources on learning should reduce the tendency to ignore or overload them.

The role of quality and quantity in the interaction process also warrants attention. Again, though designers do not reject the importance of interaction quality, conventional practice tends to emphasize tangible interaction processes, such as frequency and location, over the nature of the processing activity. Quality is the prime factor in that improvements in interaction quality tend to improve learning even when fewer responses are made. Yet, the integrated approach also views quantitative and qualitative aspects of interaction as complementary: Whereas increases in quantity alone do not influence learning positively, increases in quantity paired with qualitative increments improve learning of difficult, conceptually dense concepts. Clearly, careful consideration is required of the potential influence of both quantitative and qualitative aspects of interaction processes.

Finally, the capacity to represent conceptually the theoretical and actual allocation of resources and effort, along with associated learning effects, provides a method for estimating the consequences of tradeoffs involving effort, resources, and learning. The visual summaries generated through the model provide a dynamic method for representing the interactive contributions and limitations of model components. While the methods of representation are conceptual rather than mathematical in nature, the ability to examine interdependencies among components serves to consolidate a process that is often treated in highly segmented ways.

Although we have identified fundamental, interactive relationships among resources, effort, and learning, further research is required to determine how given interaction strategies can be expected to influence given types of learning. The model is conceptual, not prescriptive. It provides an organizing framework for interaction design, but does not suggest or prescribe the conditions under which specific interaction processes influence specific learning outcomes. As technology continues to emerge in new and powerful ways, so too must the methods and models used to optimize the interaction outcomes from such systems.

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Table 1.

Dimensions of interaction.

	Response Requirements	
Design Factors	Cognitive (Internal)	Physical (External)
Quality	Do internal responses optimize meaning, aid in organizing and integrating knowledge, and induce relevant processing?	Do overt responses match the task requirements, generate appropriate feedback, and help to activate cognitive processes?
Quantity	How much processing effort is required, how many associations must be made with existing knowledge, and how much elaboration is required for successful learning?	How many embedded questions must be provided, how often must physical responses be made, and how many repetitions are required to ensure learning?

Table 2.

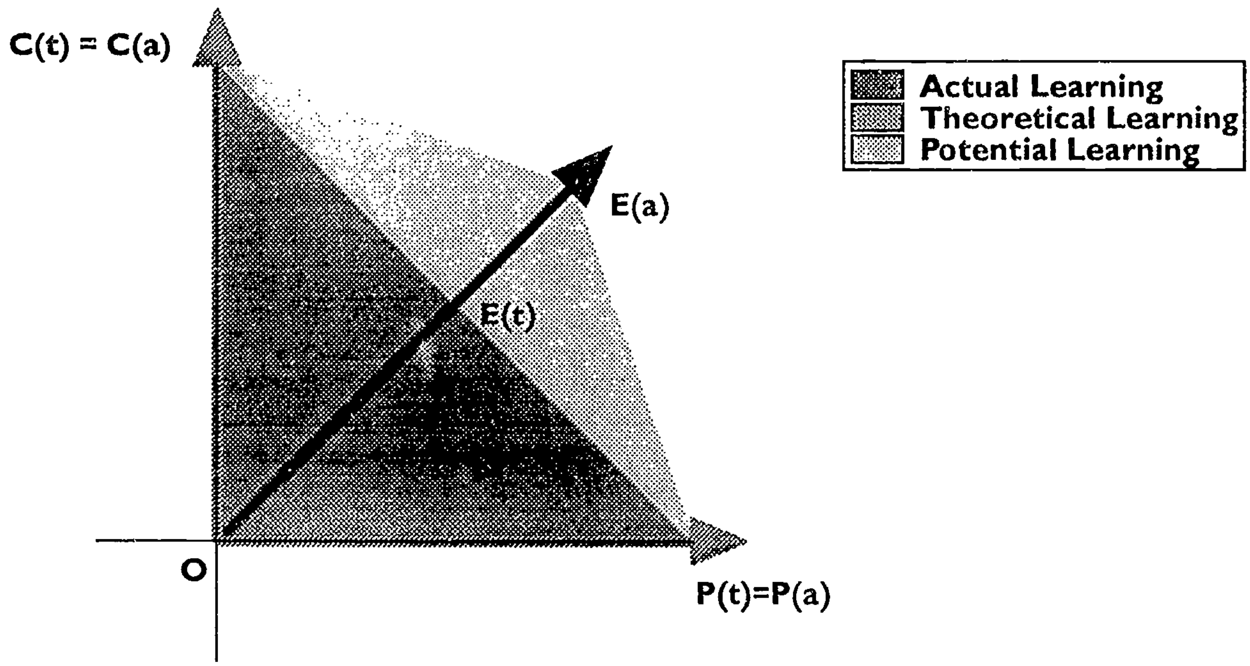
Cognitive considerations in the design of interaction strategies.

	Processing Activity	
Nature of Response	Low	High
Non-purposeful	Automatic, unconscious responses that require little or no mental effort to perform, or willful responses that are largely meaningless to the learner or task (e.g., leafing through a book, tapping fingers)	Responses that, though made with little planned purpose, require significant processing afterwards (e.g., response to accidental fire, rapid trouble-shooting to address system failure)
Purposeful	Directed responses that result in little active cognition to process (e.g., pressing the <SPACEBAR> to proceed during computerized instruction, responses to very simple embedded questions)	Responses which are made intentionally, and require significant processing activity either prior to, or as a consequence of, the response (or both before and after) (e.g., complex maneuvers during flight simulation, responses to difficult or higher-order questions or problems)

Table 3.

Relationships between mental effort and allocation of cognitive resources

	Mental Effort	
Cognitive Resources	Not Invested	Invested
Unavailable	Incoming stimuli too noisy for interpretation; background knowledge deficient, so effort not invested. (Low performance, low motivation)	Noisy stimuli (external) or lack of effective strategies render efforts useless. (Hard working but unsuccessful, frustrated due to misdirected effort)
Available	Clear stimuli and/or strategies available, but no mental effort applied. (Able, but undermotivated)	Clear stimuli, good strategies provided or possessed by learner, and mental effort appropriately invested. (Able and applies effort diligently)


C(t) = C(a)
Actual Learning
Theoretical Learning
Potential Learning
E(a)
E(t)
O
P(t)=P(a)

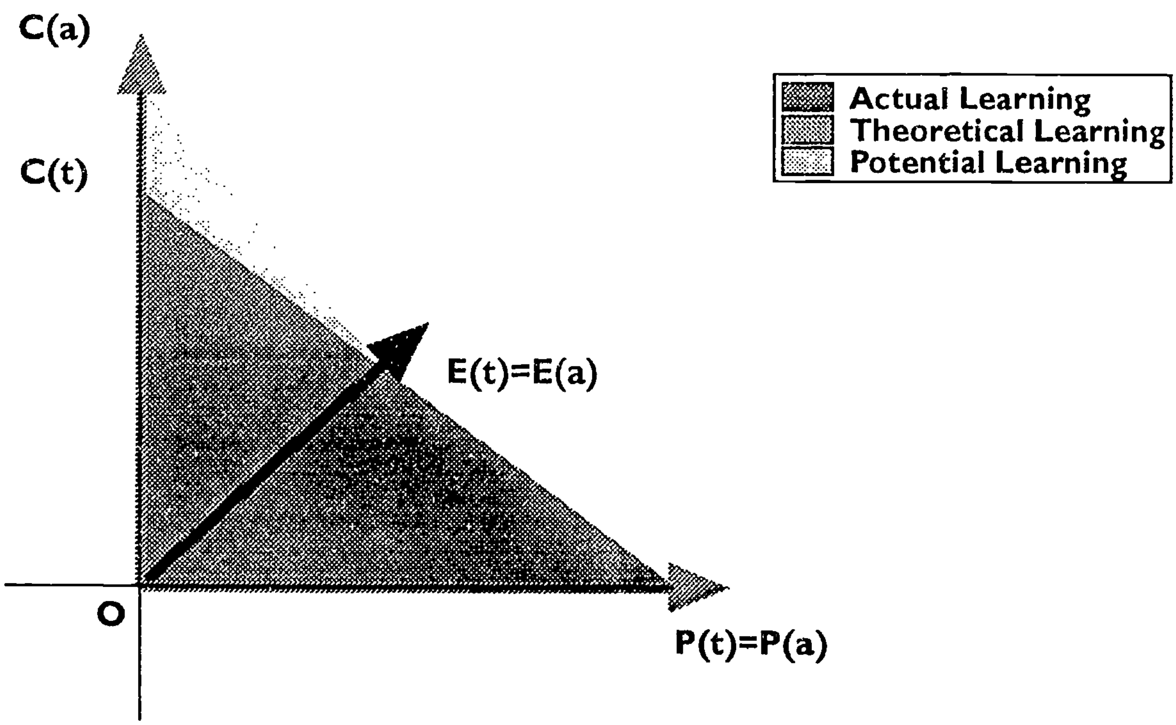

C(a)
C(t)
Actual Learning
Theoretical Learning
Potential Learning
E(t)=E(a)
O
P(t)=P(a)

Figure 7a
Excessive allocations of physical resources compared with theoretical requirements

Figure 7b
Incidental learning gain associated with an increased investment of cognitive resources

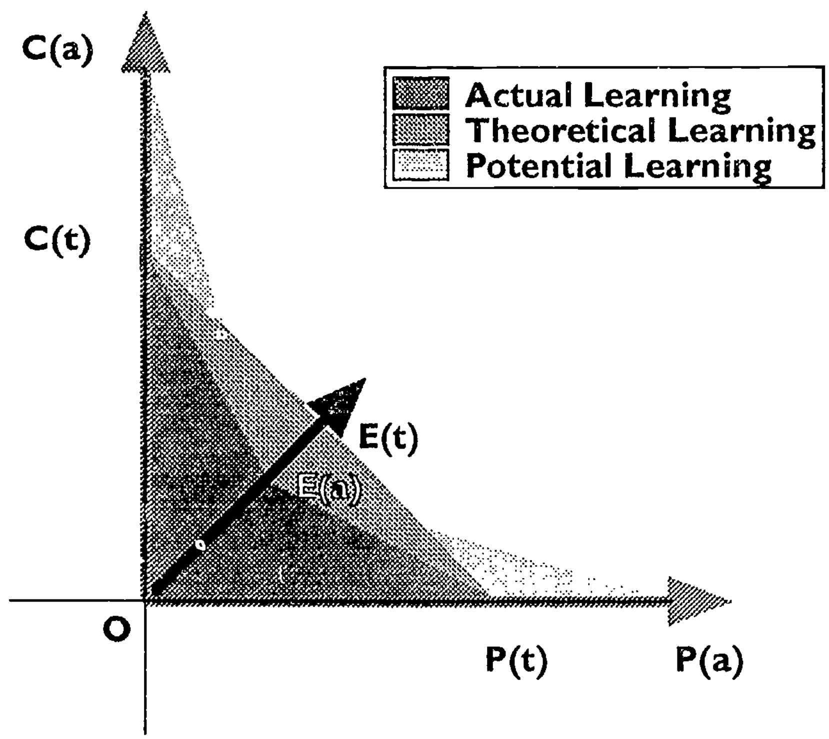

C(a)
Actual Learning
Theoretical Learning
Potential Learning
C(t)
E(t)
E(a)
O
P(t)
P(a)

Figure 6
Inability of additional resource allocations to compensate for effort deficits

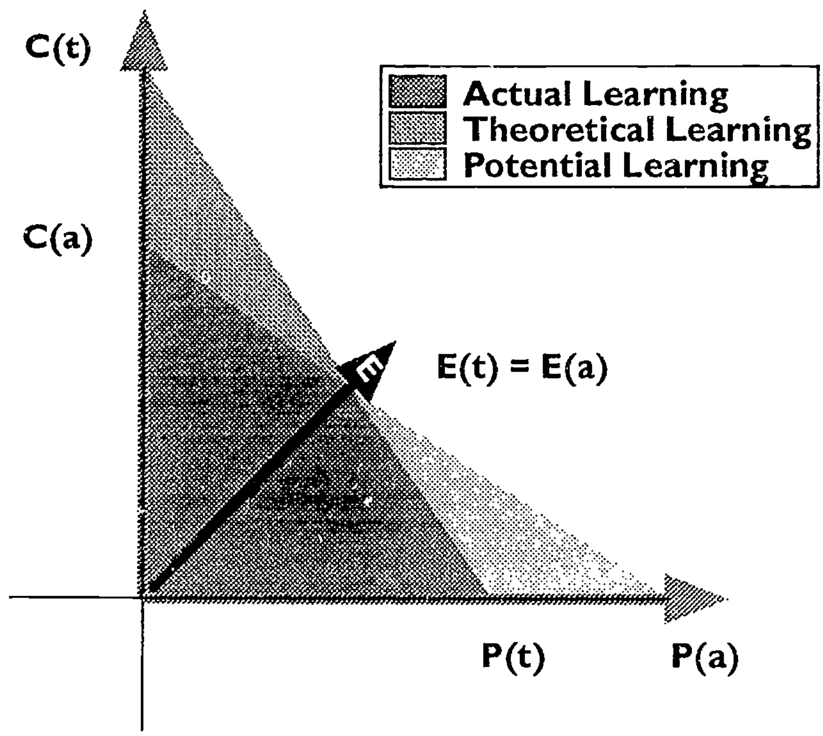

C(t)
Actual Learning
Theoretical Learning
Potential Learning
C(a)
E(t) = E(a)
E
P(t)
P(a)

Figure 5
Excessive allocations of physical resources compared with theoretical requirements

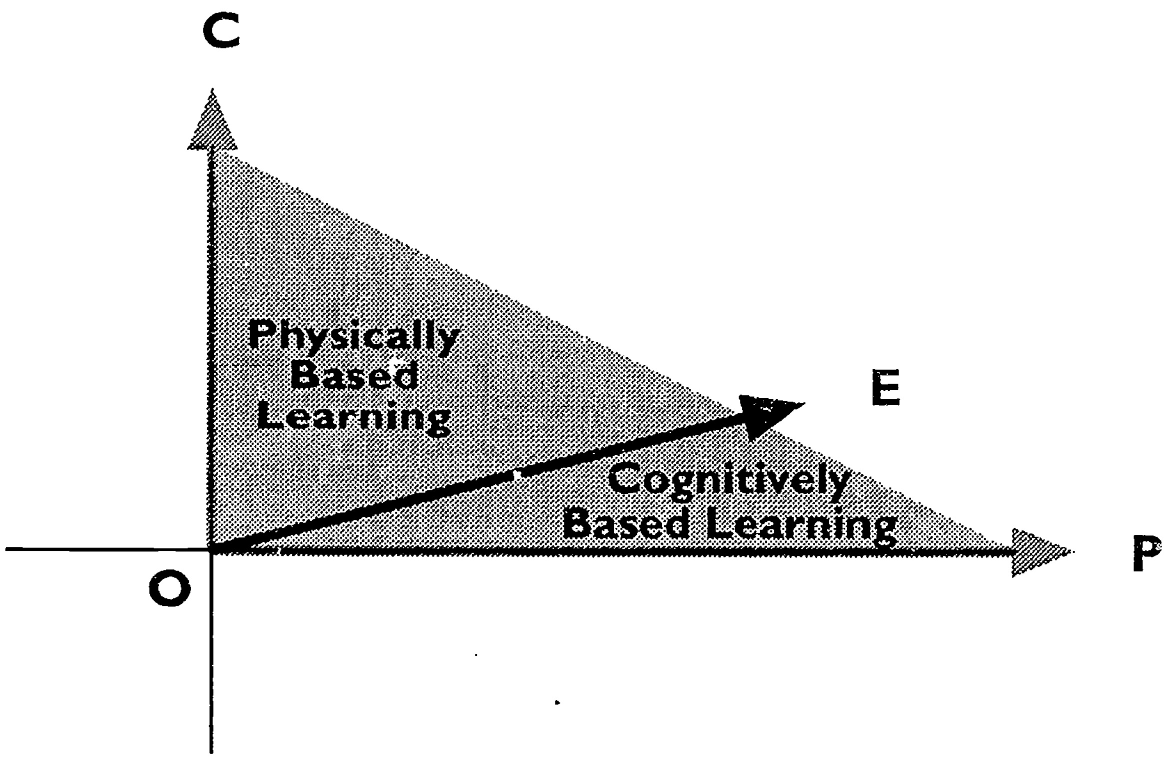

C
Physically
Based
Learning
E
Cognitively
Based Learning
P
O

Figure 4
Learning primarily influenced by the physical dimension

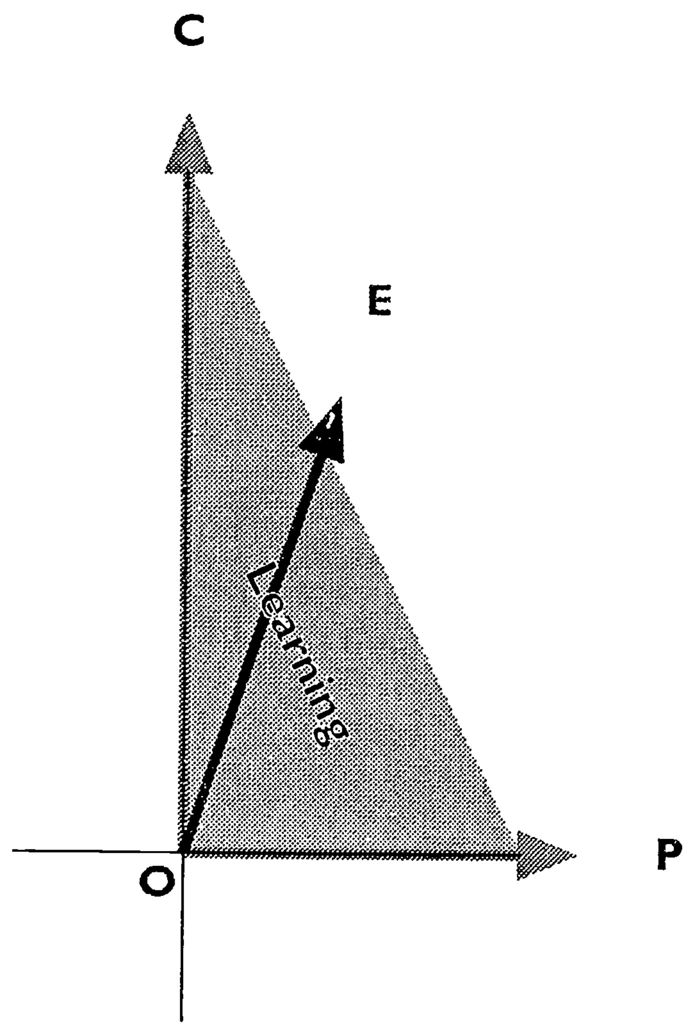

C
E
Learning
P
O

Figure 3
Interaction where the cognitive dimension contributes significantly more to learning than does the physical dimension

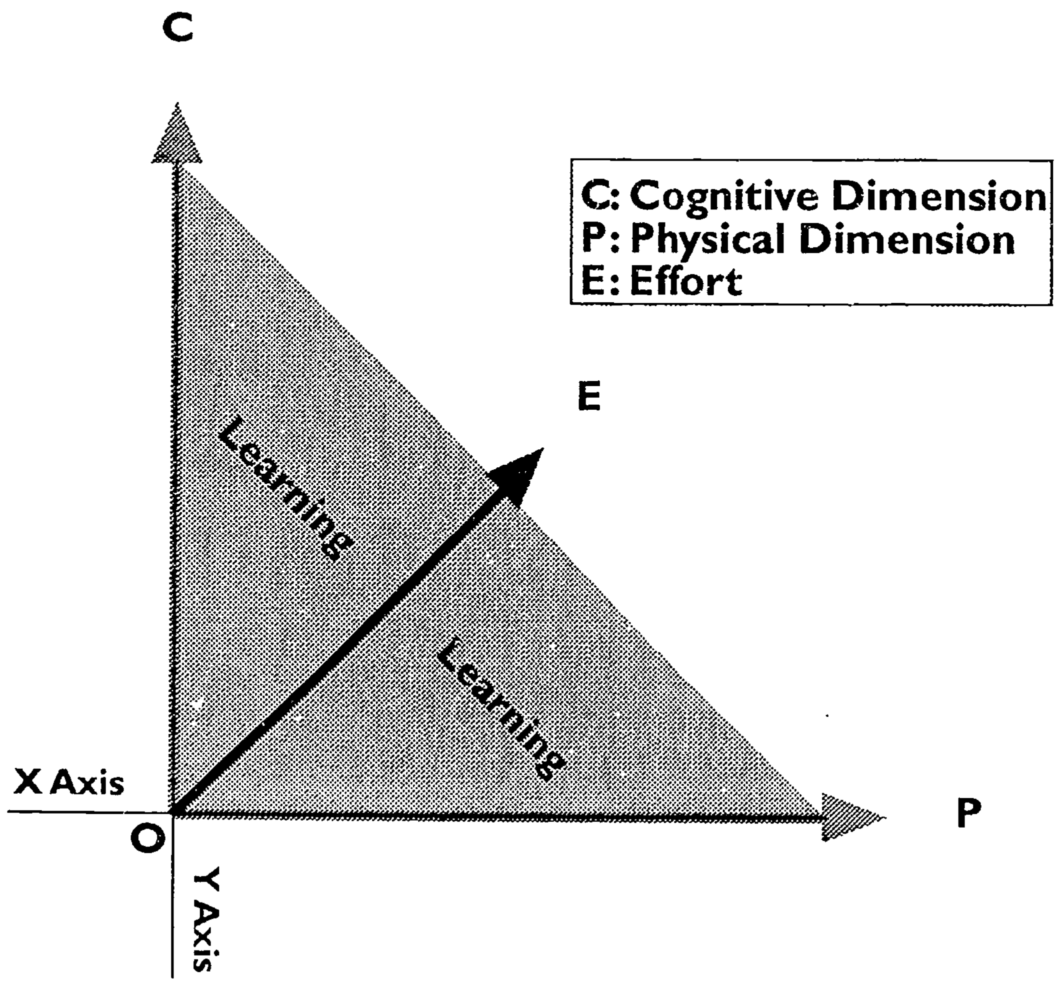

C
C: Cognitive Dimension
P: Physical Dimension
E: Effort
E
Learning
Learning
X Axis
O
P
Y Axis

Figure 2
The relationships between learning, effort, the cognitive dimension of interaction and the physical dimension of interaction

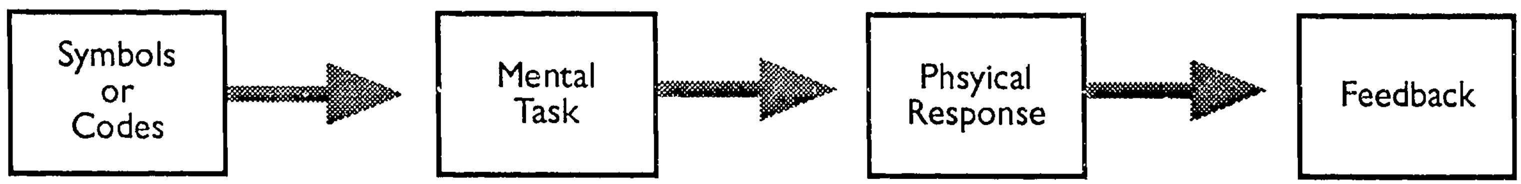

Symbols or Codes
Mental Task
Phsyical Response
Feedback

Figure I
The Relationship Between the Operational Elements of the Interaction

INTERACTION STRATEGIES AND EMERGING TECHNOLOGIES

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