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ATTENTION TO ACTION: WILLED AND AUTOMATIC CONTROL OF BEHAVIOR

Donald A. Norman and Tim Shallice

CENTER FOR HUMAN INFORMATION PROCESSING

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Attention to Action: Willed and Automatic Control of Behavior

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The major theme of the paper is that the primary role of attention is in the control of action. The basic idea is that human action sequences can run themselves off, efficiently, smoothly, without any need for deliberate attention. However, when modifications in a plan must be made, or when it is desired that some novel alternative action sequence be followed, or when it is desired to prevent some habitual act from occurring, then it is necessary for deliberate attentional intervention into the process.

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We argue that most attentional conflicts occur with the initiation rather than the execution of actions. We suggest two levels of control: a contention scheduling mechanism that selects from among competing schemas; a supervisory attentional mechanism that biases the selection process. We propose that the supervisory attentional system is required where the action sequences are ill-learned or novel, where the action is highly critical or dangerous, or where planning is required. In other cases, selection is by contention scheduling alone. The result is three modes of the control of performance: automatic, contention scheduling without deliberate direction, and deliberate conscious control. Will becomes the application of attentional resources to the control of action.

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Attention to Action: Willed and Automatic Control of Behavior

Donald A. Norman and Tim Shallice

Abstract

The major theme of the paper is that the primary role of attention is in the control of action. The basic idea is that human action sequences can run themselves off, efficiently, smoothly, without any need for deliberate attention. However, when modifications in a plan must be made, or when it is desired that some novel alternative action sequence be followed, or when it is desired to prevent some habitual act from occurring, then it is necessary for deliberate attentional intervention into the process.

We argue that most attentional conflicts occur with the initiation rather than the execution of actions. We suggest two levels of control: a contention scheduling mechanism that selects from among competing schemas; a supervisory attentional mechanism that biases the selection process. We propose that the supervisory attentional system is required where the action sequences are ill-learned or novel, where the action is highly critical or dangerous, or where planning is required. In other cases, selection is by contention scheduling alone. The result is three modes of the control of performance: automatic, contention scheduling without deliberate direction, and deliberate conscious control. Will becomes the application of attentional resources to the control of action.

Attention to Action: Willed and Automatic Control of Behavior*

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During the performance of a complex action sequence, many different action components are likely to be active at any moment. This results from the fact that any particular action sequence is apt to be comprised of numerous components that are to be performed at different times. Moreover, in the conduct of their normal everyday activities, people often interweave a number of action sequences, doing several activities during overlapping time periods. Thus, an activity such as writing a letter can occupy considerable duration, and it is performed while engaged in other activities--listening to music, conversation, eating, or drinking. The writing of the letter itself has many different levels of operation, ranging from organizational aspects to the detailed motor movements that cause the appropriate marks to appear on the paper.

The initiation of any individual action component can be relatively straight-forward; do the action as soon as the appropriate triggering conditions occur. Complications occur in setting up the appropriate conditions and analyses. Complications also occur when numerous action components compete for overlapping use of some of some limited resource or for related structures, or when the processing structures and conditions are not set up sufficiently precisely that they will perform properly without some other level of monitoring and control. In this paper we propose a mechanism that allows for several control structures to interact in order to achieve smooth non-conflicting operation of the numerous action components that might be simultaneously awaiting their turn for action. We consider separately several different aspects of the situation: first, the nature of the knowledge structures that control actions; then what we call the "horizontal threads" that specify

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attentional control; and finally, a mechanism for conflict resolution.

The Structure of the Paper

Our goal in this paper is to provide an account for both the experiential and the experimental phenomena of attention. We do this by examining what is known of the phenomena of attention and proposing a theoretical framework. The framework is structured around the notion of a set of active schemas, organized according to the particular action sequences of which they are a part, awaiting the appropriate set of conditions so that they can become selected to control action. The analysis is therefore centered around actions, primarily external actions, but the same principles apply to internal actions -- actions that involve only the cognitive processing mechanisms. The organization of this paper is first to specify the theoretical framework that will guide the later analysis, then to examine some of the phenomena of attention, first the experimental, then experiential, and finally, the neuropsychological. But before we start the theoretical framework, a brief review of some of the experiential phenomenology that surrounds the use of the term "automatic" is appropriate, for this conception plays a major role in the development of our ideas.

Automatic Performance

The term "automatic" is one of the more ubiquitous in the phenomenology of attention. However, the term has a number of different, though related, meanings. Experientially, there are at least three different meanings to the term. First, there is the way that certain tasks can be executed, without awareness of their performance (as in walking along a short stretch of flat safe ground). Second, actions may be both initiated and performed without deliberate attention or awareness (as in the automatic brushing away of an insect from one's arm). Third are cases like the orienting response, in which attention is drawn "automatically" to something, with no deliberate control over the direction of attention.

In addition, there are cases in which one can be passively aware of performing the actions, but without placing deliberate attention to them, and without any attempt to control them; an example of this latter type occurs in the performance of a skilled athletic task, where one might consciously be attending to the opponent, but be fully aware of the "automatic" hitting of the ball. Finally, within contemporary cognitive psychology, the term "automatic" is often defined operationally to refer to situations in which a task is performed without interfering with other tasks. In this situation, automatic is defined to mean that the task is performed without the need for limited processing resources (Shiffrin & Schneider, 1977).

The different uses of the term "automatic" require different explanations. We return to this point after we have outlined the theoretical framework. Basically, however, the model that we propose presumes that many action sequences are performed without any need for conscious awareness or attentional resources. It is only during the initiation or termination of sequences that attention is apt to be required, and then only with ill determined, or poorly learned tasks, or when the situation is determined to be critical or dangerous. The different senses of the term reflect different aspects of the mechanism, resulting from whether the control is entirely without attentional resources, or requires supervisory control, or attentional monitoring.

Relationship to Previous Work

The theoretical ideas developed in this model are consistent with a number of developments in the psychological literature on attention and the control of action. The emphasis that attentional limitations will have their major effect at the action end of analysis, with considerable parallel and non-conflicting processing prior to the initiation of action, is related to work of Keele (see the chapter by Keele & Neill, 1978). The basic notion that attentional processes play an overseeing role, activating whatever processing component is in need of supervisory assistance, has been suggested by LaBerge (1975), LaBerge and Samuels (1974); and Klein (1976). It is related to Posner's views of attentional biases providing costs and benefits in the production of responses (Posner, 1978). Our resource notions originate with Kahneman (1973), elaborated by Norman and Bobrow (1975) and Navon and Gopher (1979). Shallice's earlier work on the role of consciousness and action systems (Shallice, 1972, 1978), Norman (1981) on schemas and control structures, and Rumelhart and Norman (Note 3) on typing have played major roles in the theory that we have developed. The notion of schema has, of course, been around for a while, being introduced for motor actions by Bartlett (1932) and used for this purpose by Schmidt (1975). A more complete view of the views of schemas consistent with our usage is presented by Rumelhart and Ortony (1977).

A Theoretical Framework for the Analysis of Attention

Schemas and Processing Structures

Action sequences are complex ensembles of coordinated motor responses, oftentimes requiring some mental computation and decision making and considerable use of knowledge from the memory systems. We assume that specification of the components of actions and processing is done by means of numerous memory schemas, some organized into hierarchical or sequential patterns, others in heterarchical or independent parallel (but cooperating) patterns. Any given action sequence that has been well-learned is represented by an organized set of schemas, with one -- the <u>source schema</u> -- serving as the highest order control. The term "source" is chosen to indicate that the other component-schemas of an action sequence can be activated via the source. The procedural aspects of schemas require processing structures that carry out the operations specified, resulting in actions either upon an internal data base or upon the outside environment via the limbs and speech organs.

Conflicts in action sequences can arise for numerous reasons: several actions might require incompatible use of the same processing structures (as in simultaneously attempting to raise and to lower the hand); an action might require a difficult and unpracticed use of related structures (as in reaching for an object while making a precise movement of the leg); the action could require resources in excess of the capacity of a particular structure (as when attempting to do complex mental arithmetic while also retaining some items in short-term memory); or the result of one activity might preclude successful completion of another (as when eating dinner at location A precludes eating dinner at location B). Part of the difficulty in selection and scheduling of action components is to avoid incompatible or conflicting use of processing structures and to prevent the joint occurrence of other competitive activity. We propose that this occurs through selection, competition, and negotiation among schemas.

In the model there are three different states of a schema: dormant, activated, and selected. The state of dormancy is the normal, neutral state of the schema: a schema is dormant when it resides within the permanent memory structure, playing no role in the ongoing active processing of the moment. A schema is activated when it is set up, brought to a state of readiness and given an activation value. The activation value is determined by the combination of several factors, including the value given to it at set up by its source schema, the results of deliberate attentional activation or of motivation, the influence of the interaction with other activated schemas, and the goodness of match of the conditions within the trigger data base to the trigger conditions specified for the individual schema which determine the conditions under which it should be invoked. A schema is selected when its activation value is sufficiently high to exceed its own threshold. A selected schema controls actions, both internal processing and external movements of effectors.

We now describe these aspects in more detail and introduce an interaction of horizontal and vertical thread structures, and scheduling mechanisms.

Horizontal Threads

Start by considering a simple, self-contained, well-learned action sequence, perhaps the act of depressing a response switch upon the flashing of a particular light. This action sequence can be represented by a set of component schemas, triggered by the arrival of the appropriate perceptual event and resulting in the selection of the proper body, arm, hand, and finger movements to depress the button. Some or all of this processing sequence could be set up in advance by activation of the appropriate source schemas which in turn activates the detailed component schemas for carrying through the desired sequence of action upon the specified flash of light. [1] Whenever the action sequence is set up,

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1. Just how much of the details of an action square can be preset is a point that needs to be empirically examined. The observation that the latency of a response is proportional to its complexity argues against

its representation by means of action schemas constitutes a horizontal thread. The important point is that the processing structure can in principle be well specified.

The general nature of the processing structure for a simple action sequence is shown in Figure 1. The essential components are shown in the horizontal grouping of component schemas for an action sequence: this is a horizontal thread of processing structures. In this example, four component schemas are shown, receiving information about sensory and motor activity from a "trigger data base" and making use of "psychological processing structures" in transforming their outputs into actions. For many actions, the specific processing units involved would be much more complex. Thus in the skilled operation of a motor skill such as writing to dictation, a complex set of specific processing units would be involved, including storage buffers of various sorts (see Ellis, 1980; Morton, 1980; Wing, 1978). Moreover in such skills, the conceptual relations among processing units and the initiation and execution of component schemas would be considerably more complex than the linear relation shown in Figure 1. However, we let the schematic conceptualization of the horizontal thread symbolize the specification of the processing structures, regardless of their actual complexity. A horizontal thread, therefore, stands for the specification of the components of the processing structures that control the over-learned aspects of action.

In general, there will be a number of different action sequences being performed at any given time, each specified by its own horizontal thread structure, as shown in Figure 2. The operations performed by the component schemas that comprise the horizontal threads include internal operations upon a memory data base, the formation and set up of other schemas or processing threads, and external operations such as speech or movement. Different component schemas might all access a common memory data base, and they might need to use the same processing mechanisms (e.g., the same memory structures or particular muscle groups). As a result, the different threads may interact with one another, as symbolized by the lines in Figure 2 interconnecting the threads. These interactions are important for the contention scheduling mechanism (to be described later).

Schema Selection Mechanisms

When numerous schemas are activated at the same time, some means needs to be provided for selection of a particular schema when it is required for its action sequence. At times, however, there will be conflicts among potentially relevant schemas, and so some sort of conflict resolution procedure must be provided. This is a common problem in any information processing system where, at any one moment, several

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full, detailed specification of the motor schemas prior to the trigger signal (Kerr, 1975; Sternberg, Monsell, Knoll, & Wright, 1978). Our concern is independent of this consideration.

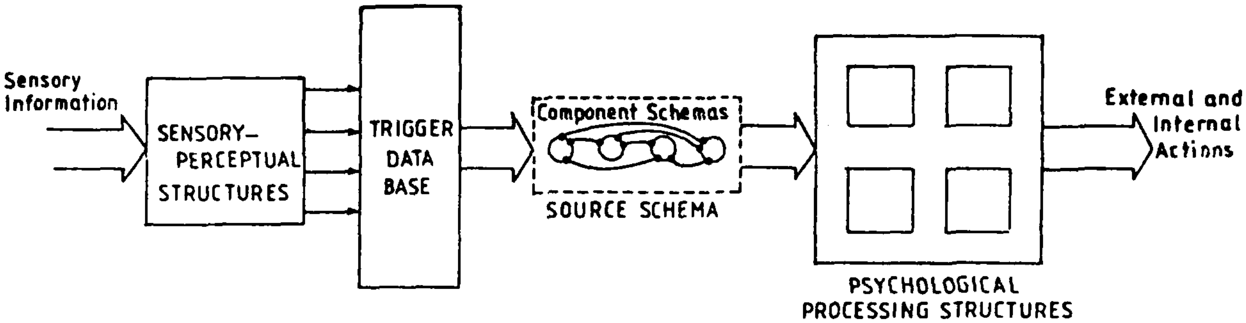

Figure 1. A Horizontal Thread. For well-learned, habitual tasks an autonomous, self-sufficient strand of processing structures and procedures can usually carry out the required activities, without the need for conscious or attentional control. Selection of component schemas is determined, in part, by how well the "trigger conditions" of the schema match the contents of the "trigger data base." Such a sequence can often be characterized by a (relatively) linear flow of information among the various psychological processing structures and knowledge schemas involved: a horizontal thread.

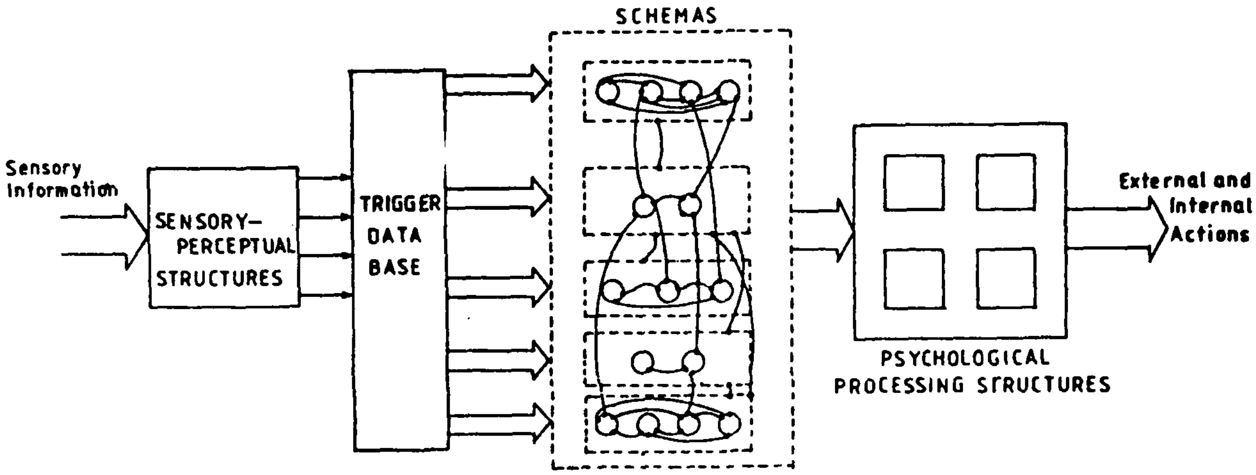

Figure 2. Simultaneous Horizontal Threads. A person often performs several tasks at the same time, with the individual components of each task either being simultaneous or overlapping in time. Moreover, any given task may last for a considerable amount of time. This figure shows 5 different horizontal threads that might be active at one time. Some means of selecting the individual schemas at appropriate times while providing some form of conflict resolution becomes necessary. The interaction among the various horizontal threads needed for this purpose is indicted by the lines that interconnect schemas from different threads.

potential candidates for operation might require access to the same resources or might result in incompatible actions. (McDermott & Forgy, 1978, discuss this issue for production systems and Bellman, Note 1, discusses the problem with respect to animal behavior.)

The procedure we propose is constrained by the desire to transmit priorities by means of the single variable of amount of activation, a concept consistent with current psychological theory. We propose that the individual component schemas of the horizontal threads each have an activation value that is determined by a combination of factors, some that operate among schemas, some that result from special processes that operate upon the schemas.

We divide the activational influences upon a schema into three sets: vertical thread influences, contention scheduling influences, and trigger condition influences. Horizontal threads determine the organizational structure of the schemas and processing mechanisms for a particular action sequence. Vertical threads determine biases acting upon the selection process. Trigger conditions determine the appropriate timing for the initiation of schemas, and the contention scheduling mechanism combines these various influences and selects between candidate schemas where appropriate.

Vertical Threads

The horizontal thread specifies the organizational structure for the desired action sequence. However, a scheme may not be available that can achieve control of the desired behavior, especially when the task is novel or complex. In these cases, some additional control structure is required. The vertical thread influences provide one source of control upon the selection of schemas, operating entirely through the application of activation values to the schemas that can bias their selection by the contention scheduling mechanisms. There are two major vertical factors: motivational variables and attentional control. It is this latter factor that is the focus of this paper. The overall system is shown in Figure 3.

Attentional resources. Deliberate attentional control is the most important of the vertical thread influences. Here we postulate that a supervisory attentional mechanism is capable of monitoring the overall activity, then of supplying an increase or decrease in the activation values of the relevant schemas. Note that this is an indirect means of control of action. Attentional control is directed only at activation value, not directly at the selection. Moreover, it is control overlaid on top of the horizontal thread organization. When attentional activation of a schema ceases, the activational value will revert to its normal value.

Allport (1980) has criticized a wide range of attention theories for succumbing to what he calls the "GPLCCP" belief in a "General-Purpose Limited Capacity Central Processor." We agree with much of his criticism, and our proposal is meant, in part, to overcome these

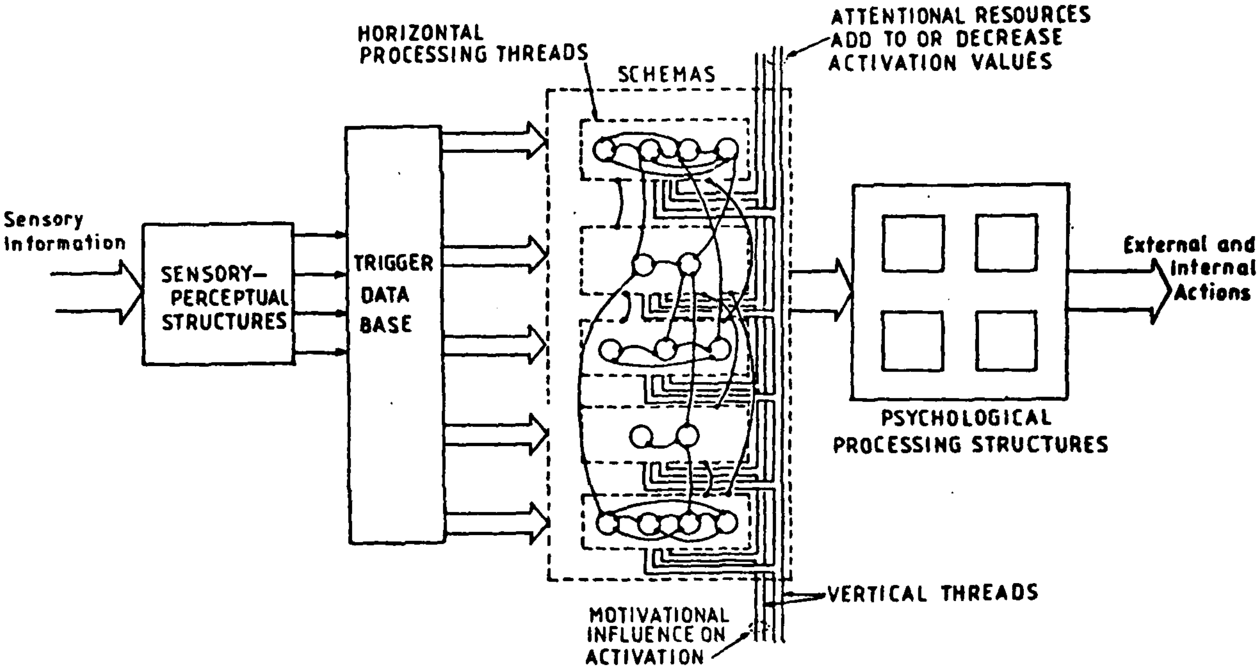

Figure 3. Vertical Threads. When attention to particular tasks is required, either because the components of the relevant horizontal threads are not sufficiently well specified or because some critical or dangerous situation is involved, then vertical thread activation comes into play. Attention operates upon schemas only through manipulation of activation values, increasing the values for desired schemas, decreasing (inhibiting) the values for undesired ones. Thus, attentional processes oversee and bias ongoing action by alteration of activation values. Motivational variables are assumed to play a similar role in the control of activation, but working over longer time periods.

criticisms. The horizontal processing threads represent particular strategies for performing tasks, making use of whatever processing structures seem needed. Several such threads may operate simultaneously provided that no related processing structures are simultaneously required and provided all the schemas involved are well-learned. Horizontal thread control is not subject to Central Processor limitations.

The model does contain a general purpose limited capacity mechanism, a supervisory attentional mechanism whose influence is felt by threading its way vertically across the active schemas. Mechanisms that are concerned with planning or monitoring of actions as contrasted with the detailed execution of the task solution can play important roles in overseeing the satisfactory operation of complex systems. Thus, such mechanisms have been incorporated into a number of models of problem solving programs (Boden, 1977; Fahlman, 1974; Sussman, 1975). In the present model, this mechanism only serves as a mediating influence; it can only modulate the flow of processing. Oftentimes, this modulation is critical for the successful operation, and whenever this is the case, central processing limitations can occur. But we presume the whole action system refines itself through experience, developing and adjusting the horizontal thread structures to minimize the need for central, vertical thread modulation.

Motivation. A second vertical thread component results from the effects of motivational factors. We take this to be a relatively slowly acting system, working primarily to bias the operation of the horizontal thread structures towards the long-term goals of the organism by activating source schemas (and through their selection, component schemas). Memory organizational procedures, for both storage and retrieval, are themselves horizontal thread structures, and so are susceptible to motivational biases.

Contention Scheduling

Simultaneously performed actions are sometimes in conflict with one another, but at other times can be jointly performed by cooperative action. In the case of conflict, when one task is started, something must prevent simultaneous performance of the other. But with cooperative tasks, the situation is quite different. Oftentimes the lower-level activities required for a single, higher level task are both cooperative and in conflict. To see this, consider how a skilled typist types the word "very" (using a standard typewriter keyboard): the positioning of the hands and fingers is both cooperative and competitive. The typing of the "v", "e", and "y" is cooperative; as the left index finger positions itself to type the "v", the middle finger of the left hand can start its movement towards the "e" and the right index finger can position itself for the "y". The hands and arm position themselves so as to assist in the finger movements. In contrast, the typing of the "v" and the "r" is competitive, both requiring conflicting use of the same finger. Analyses of high speed moving films of skilled typists indicates that both competitive and cooperative interactions occur (Gentner, Grudin, & Conway, Note 2).

To permit simultaneous action of cooperative acts and prevent simultaneous action of conflicting ones is a difficult job, for often the details of how the particular actions are performed determine whether or not they conflict with one another. Thus, whether or not several objects can be picked up at one time with the same hand is determined by the shape and location of the objects, the exact use that is made of the fingers, and the skill and experience of the person. Some sort of conflict resolution mechanism must come into play to resolve these issues.

We propose that the scheduling of actions takes place through what we call "contention scheduling," in which active schemas interact with one another through inhibition and, to a lesser extent, excitation of activation values. The result is competition for selection, modulated by the vertical thread activations, preventing competitive use of common or related structures and negotiating cooperative, shared use of common structures or operations where that is possible. (This principle is used by Rumelhart & Norman, Note 3, in a model of the hand and finger interactions in skilled typing.)

We assume that the initial activation values of component schemas are determined by means of their source schema. For example, when the source schema for a task such as driving an automobile has been selected, all its component schemas become activated, including schemas for such acts as steering, stopping, accelerating, slowing, overtaking, and turning. Each of these component schemas acts as a source schema, activating its component schemas (braking, changing gear, signalling). The one remaining consideration for the selection process is the satisfaction of the contention trigger conditions.

Trigger conditions. The determination of the activation level of a schema from higher-level systems is normally not sufficient to provide adequate timing of its selection. A particular action must be done at a time dependent upon the occurrence of appropriate environmental events. We propose that proper timing of schema selection depends upon the satisfaction of trigger conditions that specify the exact conditions under which selection is appropriate. Trigger conditions then contribute to the overall activation of the schema. How well the existing conditions match those trigger specifications determines the amount of activation contributed by this factor. (Attentional or motivational influences on activation value can override the effect of the trigger conditions, causing selection even in the absence of appropriate triggering conditions, or inhibiting selection even when there is perfect match of triggering conditions.)

The selection mechanism. There are two basic principles of the contention scheduling mechanism: first, the sets of potential source schemas compete with one another in the determination of their activation values; second, the selection takes place on the basis of activation value alone -- a schema is selected whenever its activation exceeds a threshold value. The threshold can be specific to the schema, and could become lower with use of the schema.

The competition is effected through lateral activation and inhibition among activated schemas. What degree of lateral inhibition exists between schemas on the model remains an open issue. Schemas which require the use of any common processing structures will clearly need to inhibit each other. Yet the degree of inhibition cannot be determined simply a priori. Thus some aspects of the standard refractory period phenomena can be plausibly attributed to such inhibition between schemas; explanations based upon conflicts in reponse selection fit the data well (Kahneman, 1973). However, one cannot just assume that responses by each of the two hands inevitably involve a common processing structure, as refractory period effects can disappear if highly compatible tasks are used (Greenwald & Shulman, 1973). On the model, as a task becomes better learned, the schemas controlling it could become more specialized in their use of processing structures, reducing potential structural interference and minimizing the need for mutual inhibition among schemas. At the same time, a factor that may operate to broaden lateral inhibitory interactions among schemas is the possibility of interactions among anatomically related subsystems, even when they are functionally distinct (Kinsbourne & Hicks, 1978).

Simultaneous selection of two schemas is unlikely for two reasons. First, if the two are at all incompatible, lateral inhibitory processes will tend to reduce the chance of at least one reaching threshold, as such effects magnify existing activation differences. The decrements will be greater the less well learned and, hence, the less specific the schemas are. Second, if deliberate attention is required to activate them sufficiently for selection, there will be competition for the limited resources of the supervisory attentional mechanism. This will be especially the case when tasks are not well learned. An ill-learned schema is itself a poorly integrated group of element schemas, and the supervisory attention mechanism will need to boost all the elements rather than the single whole. [2]

Note that the operation of a selected schema continues, unless actively switched off, regardless of what value its activation may have fallen to, until it has satisfied its goal, completed its operations, or until it is blocked when some resource or information is either lacking

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2. Although simultaneous selection of two schemas is unlikely, simultaneous and synchronized performance of two action sequences is quite possible. If a person needs to perform two action sequences concurrently, both of which require conscious attention, then the simplest way to accomplish this is to establish a single, higher-order source schema that oversees both actions. Then, "attention" need be directed only at a single schema. If the underlying component schemas are automated (so they need not pass through contention scheduling), the result will be synchrony in action. Thus, in general, actions that require attentional control must either be performed with exact synchrony or in alternation, first one, then the other.

or is being utilized by some more highly activated schema. The activation value is important primarily in the selection process and when the selected schema must compete for shared resources, or in providing component schemas with initial activation values.

The scheduling is therefore quite simple and direct. No direct attentional control of selection is required (or allowed). Deliberate attention exerts itself indirectly through its effect on activation values. All the action, therefore, takes place in the determination of the activation values of the schemas.

Fine timing of operations. A critical component of the performance of many skills is fine timing of the operations. As the selection mechanism is now constituted, it cannot be counted upon to respond as precisely as is required. Even if triggering conditions were the same on different occasions, the contention selection mechanism would be apt to lead to variability in selection time, in part because it would be unreasonable to assume that other factors affecting activation level were constant.

One possibility is for the contention scheduling mechanism to be used only for initial selection of schemas and for crude timing. Precise timing would then be handled by means of specific triggering conditions at appropriate (low) levels of component schemas. Component schemas would then specify precise triggering conditions required for the actions under their control so that this level of control would not be done by the contention scheduling mechanism. This assumption also allows negotiations among schemas that are simultaneously operating to take place at this same level, so that one schema operates in such a way as to allow as much as possible of the other schema to be realized. Thus, if both a paper-picking-up schema and a pencil-picking-up schema are operative, the hand and finger configuration used for picking up the paper is likely to be modified so as to allow for the picking up of the pencil with the unoccupied fingers.

The Interpretation of the Phenomena

A key component of our theory is the role of attention to action. However, many of the experiments that have been performed to examine attentional phenomena have concentrated upon the role of attention in perception. As a result, many of these experiments do not test our ideas directly, but rather require explanations that cut across the several theoretical mechanisms that we describe.

One major class of phenomena do fit reasonably directly into the theoretical structure of the model. These are certain of the phenomenological aspects of attention, which are subject to reasonable agreement among observers, but available only through introspection rather then hard experimental evidence. In this section of the paper we discuss both the experimental and the introspective, phenomenological evidence.

The Experimental Literature

According to our framework for the control of action, simultaneous tasks interfere with one another in one of two ways: structural interference, when two horizontal threads overlap in their demands for processing structures; and attentional or resource interference, when attentional capacity is required from the vertical thread. One can attempt to control both these forms of interference, the structural interference through the appropriate design of the tasks that are to be performed at the same time, the attentional interference through sufficient (albeit lengthy and tedious) training on the tasks so that they can be performed "automatically," without the need for attentional biasing of the contention scheduling mechanism.

The best way to assess these ideas would be to have experiments that separate cleanly the demands placed upon horizontal and vertical thread components. We expect attentional limitations to effect only vertical thread processes and structural interference to affect only horizontal thread influences. However, as we discussed earlier, the structural interference between any pair of tasks cannot readily be determined a priori. Thus, the existence of interference between tasks does not speak directly to the theory. Rather, the more important predictions concern the conditions for which there will be no interference between tasks, as this requires that there be neither structural (horizontal) nor attentional (vertical) interference.

Simultaneous tasks. On the model, satisfactory performance of several simultaneous tasks depends upon lack of conflict of these tasks for any of several kinds of resources. The major prediction is that parallel dual-task performance should be most easily possible where only a single action sequence has to be initiated, that is, where only one schema has to be selected by contention scheduling. This fits with the results on monitoring (for review see Duncan, 1980). Thus Moray and Fitter (1973) and Sorkin and Pohlmann (1973) showed that monitoring for one of several possible signals (or signals over several possible channels) could be done satisfactorily, and that performance suffered only when simultaneous target detection and responding was required (in our terms, when there was initiation of actions).

Effective multiple channel monitoring depends on the activation of appropriate schemas by triggers that have been set up previously. There can, however, be difficulties in setting up the schema trigger conditions so as to match the expected signals unambiguously. For instance, how novel may the set of trigger conditions be? The Shiffrin and Schneider experiment (1977) in which the "automatic" attention was not possible when the target distractor relation was varied from trial to trial indicates that considerable practice is required to set up some trigger conditions. A second problem is that activation-based processes are liable to result in selection induced by stimuli similar to targets. The experiments by Treisman and Gelade (1980) seem to indicate that some situations which require the integration of "separable features" (where the background distractors may also contain these same features) present special difficulties of this sort. Thus, in some cases, effective target selection cannot be performed without internal processing actions. On the current model this is apt to require attentional activation of the processing schemas, thus forcing deliberate serial attention to be directed at the parts of the signal.

Simultaneous performance of tasks which require production of separate response streams is possible when two conditions are satisfied: first, the horizontal thread structures must be sufficiently developed that they can control the action sequences without deliberate supervision; second, there cannot be any structural interference. The first condition is obviously most apt to be satisfied when there has been considerable practice at the tasks. The second condition requires minimization of the overlap of use of common processing or control mechanisms. These conditions have been satisfied in a number of experiments that have examined performance of highly skilled, well-practiced people (Allport, Antonis, & Reynolds, 1972; McLeod, 1977; Spelke, Hirst, & Neisser, 1976).

Even in these situations, performance often deteriorates somewhat when a second task is added, although there appears to be no obvious grounds for structural or attentional interference. A common explanation of this finding is that there is an excess "overhead" associated with the performance of two tasks rather than one, an overhead that leads to a performance decrement regardless of the nature of the tasks (e.g., Allport, 1980). The model provides a possible source for this extra overhead: the supervisory attentional mechanisms. Unless the second task is extremely well-learned, there will be a need for extra source and component schemas that require vertical thread activation in their setup and in their selection. Thus, as Allport (1980) pointed out, in experiments involving piano playing conducted by Allport, Antonis, & Reynolds (1972), the one subject who showed no interference "was also the most competent of our pianists." The other subjects all found some technical challenge in the music such that "moments of emergency occurred," where recovery required some relatively unpracticed applications of keyboard technique and therefore, on our model, attentional resources.

Attentional demands at the initiation of actions. A major theme of the model is that attention is used primarily at the initiation of actions. This property of the model fits with the results of probe studies during the movement, where responses to probes at the start or end of movement are more delayed than those during execution (Posner & Keele, 1969; Ells, 1973). Indeed under certain conditions, although the start of the response shows the expected interferences, the large stages of response execution may not delay responses to probes at all (Posner & Keele, 1969). In interpreting these results it is important to realize that both the starting and stopping of a response requires selection by contention scheduling since, at one level, they involve different schemas. To stop a physical motor response requires that the limb motion be halted, which requires initiation of the action of muscle groups that can counter the momentum of the movement. It is just as hard to stop a movement as it is to start it. The exception is when movement is stopped by an external "stop." In this case, one would not expect attentional effects at the termination of the movement which is exactly what is found.

Moreover, attentional influences act only to bias the selection mechanisms, not to do the selection. One relevant study was performed by McLean and Shulman (1978) who found that when attention was first directed to the possibility of a signal and then distracted, there was a residual bias that remained from the initial investment of attention. We believe this finding to be more consistent with the view that attention can only bias processing actions than with the more usual view that attention selects processing.

A related prediction made by the model is that if the triggering potential of one type of stimulus is much stronger than that of a second type, then the former will be selected in contention scheduling even though the latter is being deliberately attended to. In this situation, triggering activation is more powerful than activation from the supervisory attentional mechanisms. One set of such findings comes from the literature on selective attention in which an attempt is made to keep the subject concentrating upon a primary task while other signals are presented. A classic example of the difficulty of doing this is the Stroop phenomenon. Certain classes of words presented upon a secondary channel can intrude upon or bias primary task performance, such as a word that fits within the context of the primary channel, or that has been conditioned to electric shock, or that has high emotional value (such as one's own name). Performance of the other task is impaired when the interrupt occurs. In terms of our model, these "intrusions" result from data-driven entry of action schemas into the contention scheduling mechanism and their selection there due to the strongly activating properties of such triggers. These intrusions, therefore, are similar to the form of action slip found in "capture errors," to be discussed later.

Experiential Phenomena

An important aspect of attention and the control of action is its phenomenology. The role of the conscious awareness of directed, controlled attention to events and to actions, and the nature of those situations in which one can act without awareness or deliberate intention to act, are all of direct relevance to the theoretical structures described here. Indeed, the theory was developed with explanation of the experiential aspects of attention as much of a goal as the results of controlled experimentation.

Phenomenal reports of action provide evidence for qualitative distinctions among different types of experience. We do not discuss the correspondence between consciousness and information processing mechanisms and functions (but see Shallice, 1972, 1978). To make differentiations between types of experience, it is sufficient to assume that the supervisory attentional mechanism has the possibility for access to information about the schemas selected in contention scheduling, and that reflection on action involves this process.

Automatic performance. In an earlier section we identified several different aspects of the term "attention." On the model, there are correspondences for all these related aspects of the term. Some actions, such as the decision to walk across a certain path, might be initiated with directed attention and clear awareness, but the performance need not depend upon the supervisory attentional mechanism nor interfere with any other activated schema in contention scheduling; hence, the automatic nature of the performance. In other actions, such as the brushing away of an insect, even the initiating of the act (through data-driven excitation of a source schema) might not depend upon the supervisory attentional mechanism. In this case, there could be a complete lack of awareness of both the initiation and the action. These cases also correspond to the operational definition, for there is no demand upon the attentional resources.

There are, however, cases in which one experiential sense of "automatic" does not correspond to "automatic" in the operational sense. Thus, the orienting response is phenomenologically automatic, as there is no deliberate attentional control over schema activation and selection. However, schema selection may very well interfere in contention scheduling with the operation of tasks being performed at the same time; in these cases, the operational criterion for automaticity is not met.

A specially interesting case of automaticity is where at one time the action did require conscious direction for its performance, but now no longer does so. As William James (1890) pointed out at some length, the common denominator of such actions is that they are habitual, frequently performed, usually in a relatively fixed format. Why should the ability to perform such tasks automatically only occur when they are well learned? On the model, this is because newly learned actions are apt to be ill-specified. Their schemas are relatively small, encompassing relatively specialized sub-actions. Moreover, their triggering conditions are apt to be ill-specified, not well matched to the actual conditions that occur. As a result, continual monitoring is required by the attentional mechanisms, and selection must often be forced (or delayed) by the application of deliberate attentional activation. Well-learned actions are apt to be well specified, with their schemas encompassing large, organized units of behavior, and with their triggering conditions well-matched to the situation. As a result, once their schemas have been selected, they can maintain control effectively for longer periods.

The amount of interference that a task presents to other tasks performed at the same time will also decrease as learning improves. This decrease comes about for three different reasons. First, as the schemas become better specified, there will be fewer gaps and fewer weaknesses that need the supervisory processes for proper control. Second, as the triggering conditions become better matched to the situation, they are less likely to need supervisory attentional resources. Third, general schemas are apt to make more general demands on processing structures, making it more likely that there will be conflicts with other action sequences. As the actions become specified more precisely, they involve a smaller fraction of the psychological processing structures. This too reduces the conflicts in performance, by decreasing the possibility of lateral inhibitory conflicts during contention scheduling.

<u>Contention scheduling without deliberate direction</u>. It is possible to be aware of performing an action without paying active, directed attention to it. This corresponds to situations in which the selection of a schema is accomplished by contention scheduling without the involvement of the supervisory attentional mechanism. The most general situation of this type is in the initiation of routine actions. Phenomenally, this corresponds to the state that Ach (1905) describes as occurring after practice in reaction time tasks. Over the first few trials, he said, the response is preceded by awareness that the action should be made, but later there is no such awareness, except if preparation has been inadequate. By then, the stimulus triggers the appropriate schema without the involvement of the supervisory attentional mechanisms. In well-learned tasks, the subject experiences the response as proceeding with "an awareness of determination" even if it is not immediately preceded by any experience of intention to act. In our terms, this is because the schema controlling action had previously been activated using the supervisory attentional mechanisms. but then the schema selection occurs automatically when the proper stimulus conditions occur.

Whenever contention scheduling takes place without any present or prior involvement of the supervisory attentional mechanisms, even the "awareness of determination" is absent. Data-driven triggers act in this way. Because there is no involvement of the supervisory attentional mechanism, and hence no monitoring, errors can easily occur. Two such errors are the form labelled "data-driven errors" and "capture errors" (Reason, 1979; Norman, 1981). Both classes of errors occur when the schema that was intended to control action is replaced by another one, leading t an unintentional result. In the case of "data-driven" errors, the unintended schema is activated by perceptual information (by newly arriving sensory data). In the case of "capture errors," the unintended schema shares considerable features with the intended one, and in addition, is the more frequently performed action sequence. In either case, one may find oneself doing a totally unexpected set of actions, much to one's own dismay.

Take for example, Reason's description of the person who went to the garage to drive to work and found that he had "stopped to put on my Wellington boots and gardening jacket as if to work in the garden" (Reason, 1979). Or take the person described by William James who went to the bedroom to change for dinner and ended up undressed, ready for bed. Students of abnormal behavior may wish to point out that there is seldom a single explanation for behavior, that there are many interacting causes. Thus, the person who found himself gardening might also have (subconsciously) wished to avoid going to work. So too with the person described by James; the dinner may have been unwelcome. Our contention scheduling system is deliberately designed with these issues in mind. We postulate that selection results from the combination of numerous factors. Thus, it is quite possible that the sight of the gardening boots or the act of undressing (to change one's clothes) would not by themselves have been sufficient to have selected the discrepant behavior. Similarly, the hidden wishes, whether conscious or not, would not by themselves have been sufficient to cause the behavior. But the fortuitous combination of the wishes and the situation were sufficient to cause selection of the schemas.

Deliberate conscious control. A critical separation on the model is between action initiated through contention scheduling without the involvement of the supervisory attentional mechanism, and action initiated with the involvement of this mechanism. This distinction corresponds closely to William James's (1890) distinction between "ideo-motor" and "willed" acts. To James, "wherever movement follows _unhesitatingly and immediately_ the notion of it in the mind, we have ideo-motor action. We are then aware of nothing between the conception and the execution." These "ideo-motor" actions (a category which does not exclude "awareness of determination") corresponds directly to our idea of contention scheduling without conscious direction. His concept of actions involving "an additional conscious element in the shape of a fiat, mandate, or expressed consent" corresponds to cases where we believe the supervisory attentional mechanism to be operative.

Experientially, a number of different sorts of tasks appear to require a considerable amount of deliberate attentional resources. These tasks fit within the following categories:

(a) they involve planning or decision-making,

(b) they involve components of trouble shooting,

(c) they are ill-learned or contain novel sequences of actions,

(d) they are judged to be dangerous or technically difficult,

(e) they require overcoming a strong habitual response or resisting temptation.

The general principle involved is that these are special situations in which the uncontrolled application of a horizontal processing thread through the contention scheduling mechanism is apt to lead to error. The supervisory attentional mechanisms allow more control over the sequence of actions to be performed than is possible through horizontal thread direction alone.

Vertical thread influences are necessary because individual schemas are limited in what they can foresee and control. Further, although the contention scheduling mechanism allows selection among schemas, it does not allow for integration of information across them. Given the variety and power of human capacities, it would appear that mechanisms must exist which have available to them information about the varied needs and capacities of the organism, including source schema, the ability to monitor the operation of schemas, and the power to initiate the construction of new schemas out of existing ones.

Planning and decision making are processes that operate in the formation of intentions that are not routine. In our terms, we plan or decide when it is clear that no existing schemas are sufficient to satisfy a particular goal. In these cases, information must be from more than one schema, or new schemas must be formed. This requires involvement of the supervisory attentional mechanisms. We assume though, that these general powers are bought at the cost of speed. Use of the supervisory attentional mechanisms then provides both benefits and costs. The benefits derive from the increased processing power brought to bear on the problem at hand; in general, judgments which it controls will be superior to the unguided selections of contention scheduling. The costs result from the slowness, leading to difficulty in the control of rapid, skilled actions, and to seriality in the control of what would otherwise be parallel acts.

We define trouble shooting to be the application of planning and decision-making processes to actions already in progress. It occurs when an unexpected error occurs in the operation of an action (see Mandler, 1975). When a particular, specialized component schema has failed, one solution is to replace it with a more general one. More general schemas are apt to require selection through contention scheduling and vertical thread control by the supervisory attentional mechanisms.

The performance of ill-learned or novel skills requires what Fitts and Posner (1967) called "the early or cognitive phase ... in which it is necessary to attend to cues, events, and responses that later go unnoticed" (pp.11-12). These are situations which require attentional control because neither appropriate schemas nor their triggers have been developed. With dangerous and technically difficult situations, error is relatively costly. In this situation, one wishes to guard against the vagaries of contention scheduling and enforce selection of the most appropriate schema by means of strong activation. Similarly, in overcoming habitual responses or in resisting temptation, the appropriate schema must be strongly activated and the others strongly inhibited, else a more usual, but inappropriate act, might be selected by the normal operation of contention scheduling.

There can be costs in using deliberate control in a task that is normally performed automatically. Activation of schemas in contention scheduling by the supervisory attentional mechanism has the effect of reducing the influence of activation from triggering stimuli and other schemas in the selection process: subtle environmental control is lost. In addition, action execution must proceed unit by unit, each schema awaiting its turn for receiving attentional biases. The result is a lack of smoothness and a slowing of performance.

<u>Neuropsychological Phenomena: The Frontal Lobes</u>

There are strong correspondences between functions of our supervisory attentional mechanism and those ascribed by Luria (1966) to the prefrontal regions of the brain. If the supervisory attentional mechanism were damaged, the resulting behavior would be similar to the behavior of patients with lesions to the prefrontal regions.

A deficit in planning corresponds to Luria's clinical characterization of the frontal lobe syndrome, which has been supported in a number of experimental studies involving maze learning, complex visual-constructive tasks, and complex arithmetical problem-solving (see Walsh, 1978). The simplest example of a planning disorder is the finding of Gadzhiev (see Luria, 1966) that frontal patients when presented with a problem tend to miss out the initial assessment of the situation. Frontal lobe patients have also been characterized clinically as having deficits in initiative, in dealing with novelty, and of judgment (Penfield & Evans, 1935; Goldstein, 1936).

Patients with frontal lobe lesions have difficulties with error correction. The Wisconsin card-sorting test involves multi-dimensional stimuli where the patient must switch from sorting according to one dimension to sorting according to another. In this task frontal patients show a strong tendency to perseverate in sorting on the previously correct dimension, even when they are told they are wrong (Milner, 1964; Nelson, 1976). Perret (1974) found that patients with frontal lobe lesions are the most impaired group on the Stroop test. This is a task in which the usual response to a stimulus is not the desired one -- habitual responses must be suppressed. In this situation deliberate attentional control is required, but this in general presents especial difficulty for frontal lobe patients.

The failure to overcome an habitual response tendency is one side of the general effect that should occur on our model if the supervisory attentional mechanisms are damaged. In this case, behavior will be left under the control only of the horizontal thread structures, plus contention scheduling. In the examples above where one schema is more strongly activated than the others, it will be difficult to prevent it from controlling behavior. By contrast, when several schemas have similar activation values one should obtain another clinical characteristic of frontal patients: an instability of attention and heightened distractability (see Walsh, 1978). This apparent contradiction between increased perseveration and increased distractability results from failure of a single mechanism. Both results are observed in animals with prefrontal lesions (see Brush, Mishkin, & Rosvold, 1961; Pribram, 1973).

If the properties of the supervisory attentional mechanism seem to correspond fairly well with neuropsychological evidence, does the same apply to the properties of contention scheduling? One possible relation is between the lateral inhibitory and threshold properties of contention scheduling and certain properties of the basal ganglia, thought because of their role in the aetiology of Parkinson's disease to be involved in the initiation of action (see also Stein, 1978). Moreover the basal ganglia are innervated by dopamine systems, which it has recently been claimed mediate the selection of behaviors through a lateral inhibitory mechanism somewhat analogous to contention scheduling (see Joseph, Frith, & Waddington, 1979) and which when they malfunction (as in amphetamine psychosis) lead to disorders which could well be at the level of the selection of action (see Lynn & Robbins, 1975).

Will

We propose that "will" be the direction of action by direct conscious control through the supervisory attentional mechanism. This definition is consistent both with the popular meaning of the term and with the discussions of will in the earlier psychological literature. Thus, strongly resisting a habitual or tempting action or strongly forcing performance of an action that one is loathe to perform seems to be prototypical examples of the application of will. The former would appear to result from deliberate attentional inhibition of an action schema, the latter from deliberate activation. James (1890) drew the contrast between "what happens in deliberate action" where will is involved and actions that do not require will, where the responses followed "unhesitatingly and immediately the notion of it in the mind" (ideo-motor actions). Situations in which there is no need for will are those where there "seems to be the absence of any conflicting idea."

In our view, will varies along a quantitative dimension corresponding to the amount of activation or inhibition required from the supervisory attentional mechanisms. The assumption that this activation value lies on a continuum explains why the distinction between willed and ideo-motor actions seems quite clear when considering extreme actions, but becomes blurred when considering those that require very little attentional effort. Thus, introspection fails in determining whether or not will is involved in the voluntary lifting of the arm. But there is no need to make a distinction if this act is simply identified as being near the zero point of the quantitative scale of attentional activation.

The idea that will corresponds to the output of the supervisory attentional mechanisms has certain other useful consequences. Consider the errors that occur with brief lapses of attention, when there is a failure to sustain will adequately. One type of error results following a decision not to do a step within a habitual sequence of actions. To eliminate the step requires deliberate (willful) inhibition of the relevant schema. If there is a momentary lapse of attention to the deliberate inhibition, the step may get done anyway. Closely related is the error that occurred to one of us. Having decided not to take another bite of a delicious, but extremely rich dessert, with only a brief lapse of attention, the cake got eaten.

Certain aspects of will require elaboration of our approach. In some circumstances an action may seem to require no will at all, yet at other times, require extreme demands. Thus, getting out of bed in the morning is at times an automatic act, at other times requires great exertion of will. One explanation for this observation is that activation of an action schema by the attentional mechanisms necessarily involves knowledge of consequences. When these are negative, they lead to inhibition of the source schemas which then must be overcome. In some cases, the self-inhibition can be so intense as to prevent or at least make very difficult the intended act. Thus, inflicting deliberate injury to oneself (as in pricking one's own finger in order to draw blood) is a difficult act for many people.

The elicitation of strong activation from the supervisory attentional mechanism is not necessarily unpleasant. Indeed, many sports and games seem to be attractive because they do necessitate such strong activation. In this case "concentration" is perhaps the more appropriate experiential equivalent rather than "will." In addition, will is not just a matter of attention to actions. As Roy D'Andrade (personal communication) has pointed out, a willed act demands not only strong attentional activation, it also depends on the existence of a "mandated decision," independent of one's attending, a conscious knowledge that the particular end is to be attained. This mandate, in our view, would be required before the supervisory attentional mechanisms will produce their desired activation output. However the critical point for the present argument is that the phenomenal distinction between willed and ideo-motor acts flow from separation of the supervisory attentional mechanisms from the systems they oversee. The phenomenology of attention can be understood through a theory of mechanism.

Summary

We present a possible framework for considering the role of attention in the control of action. In this, we have emphasized several things. First, because people usually do numerous activities during a given time period, a major concern for the control of action becomes how the selection of the individual components occurs at appropriate times, allowing co-operative actions to co-occur and avoiding conflicting ones. Second, there is the importance of the initiation of action. We assign the basic role of the attentional mechanisms to the initiation of action (as opposed to perceptual analysis -- where the bulk of the experiments have been performed -- or to thought and decision processes). By "action" we include the initiation of both internal processing actions and external control of effectors. Third, we emphasize that many activities can be carried out autonomously, without the need for conscious or attentional control, by means of well-specified, horizontal thread processing components. It is only in cases where the action sequences are ill-specified, or in situations that are judged to be critical or dangerous that deliberate attentional control is required. In this case, we suggest that supervisory attentional mechanisms of limited capacity oversee the operation of the system, monitoring for the success of the activity, and biasing the selection and suppression of component schemas by altering the activation values of those schemas. We specify that such attentional control does not act directly, but only indirectly through the mediation of activation value.

By this scheme, there are two forms of interference likely to be encountered in the production of simultaneous tasks. The two forms correspond to (a) interference among horizontal threads when they must compete for use of overlapping processing mechanisms and to (b) interference among the vertical thread activations when they must be produced by the supervisory attentional mechanism. The first form of interference -- horizontal thread interference -- is related to "structural interference," but on our approach this is mediated by the operation of a mechanism, contention scheduling, that selects from potentially competing actions using only the activation levels of the schemas that control them. The second form of interference -- vertical thread interference -- is more a form of "resource interference."

There are two different modes for the control of action and, like the distinction between forms of interference, they also correspond to the difference between horizontal and vertical thread control. Thus, when processing sequences are sufficiently well specified that they can be controlled entirely by horizontal thread operations, they correspond to "automatic" actions. When conditions do not permit unsupervised horizontal control (or when the person deliberately invokes attentional processes to the action sequence), then the operations correspond to processing under "conscious control" or "willed" action.

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