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Automaticity, Resources, and Memory: Theoretical Controversies and Practical Implications

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This article describes a theoretical controversy over the nature of automaticity and suggests implications of the controversy for the design of training programs. One side of the controversy describes automaticity in terms of processing resources, in that automatic processes require little or no resources. The other side describes automaticity as a memory phenomenon dependent on direct-access, single-step retrieval from memory. The two sides differ in their ability to account for four basic questions about automaticity: (1) why automatic processing has the properties it does; (2) how automaticity is learned; (3) how the properties of automaticity emerge with practice, and (4) why consistency of practice is so important to the development of automaticity. The memory view provides better answers than the resource view, particularly for questions about training. Training is an important practical issue, and implications of the memory view for training are spelled out in some detail.

INTRODUCTION

There is a battle raging in the ivory tower over the concept of automaticity. One faction represents the "old guard," the modal view in the field, and construes automaticity as a way to overcome resource limitations. The other faction is revolutionary (or sees itself as such) and construes automaticity as a memory phenomenon reflecting the consequences of running a large data base through an efficient retrieval process. The battle may turn out to be a tempest in a teapot, affecting no more than academic promotion and tenure. Or it could be the turning point in an intellectual revolution that reaches far beyond the ivory tower to the most practical nooks and crannies in the land.

The purpose of this article is to describe the battle as it has developed so far, sketching each position and speculating on the outcome, and to suggest what the world would be like if the revolutionary position were even partly true. The idea that automaticity is a memory phenomenon has many implications that may prove important in practice even if the old guard maintains its hold on the ivory tower. Automaticity is a major factor in skill acquisition, so new perspectives on automaticity may shed light on practical issues in training.

FACTS ABOUT AUTOMATICITY

Empirically, automaticity is reasonably well understood. There are a number of basic

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facts, well documented and replicable, upon which both sides agree. Disagreement arises over the interpretation of the facts. What follows is a brief review describing the major phenomena that theories of automaticity must address. For more extensive reviews, see Kahneman and Treisman (1984), LaBerge (1981), Logan (1985a), and Schneider, Dumais, and Shiffrin (1984).

There is considerable evidence that automatic processing differs from nonautomatic processing in several respects. Automatic processing is fast (Logan, 1988; Neely, 1977; Posner and Snyder, 1975); effortless (Logan, 1978, 1979; Schneider and Shriffin, 1977); autonomous or obligatory (Logan, 1980; Posner and Snyder, 1975; Shiffrin and Schneider, 1977; Zbrodoff and Logan, 1986); consistent or stereotypic (Logan, 1988; McLeod, McLaughlin, and Nimmo-Smith, 1985; Naveh-Benjamin and Jonides, 1984); and unavailable to conscious awareness (Carr, McCauley, Sperber, and Parmalee, 1982; Marcel, 1983).

There is also abundant evidence that automaticity is learned, which is what makes it relevant to skill acquisition and training. Some have argued that automaticity is a limiting factor in skill acquisition, that the rate at which components are automatized limits the rate at which skill is acquired (Bryan and Harter, 1899; LaBerge and Samuels, 1974). Practice in consistent environments seems to be a necessary condition in order for learning to occur (Fisk, Oransky, and Skedsvold, 1988; Logan, 1979; Schneider and Fisk, 1982; Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977; but see also Durso, Cooke, Breen, and Schvaneveldt, 1987). Most of the properties of automaticity emerge through practice in consistent environments (Logan, 1978, 1979; Shiffrin and Schneider, 1977).

The major questions to be answered by theories of automaticity are as follows: (1) Why do automatic processes have the previously mentioned properties? (2) How is automaticity learned? (3) How do the properties of automaticity emerge with practice? and (4) Why is consistency important? Theories differ markedly in the answers they provide and even in their ability to provide answers.

THEORETICAL APPROACHES TO AUTOMATICITY

Thesis: Automaticity and Resources

According to the modal view, automatic processing is processing without attention, and the development of automaticity represents the gradual withdrawal of attention (Hasher and Zacks, 1979; Logan, 1979, 1980; Posner and Snyder, 1975; Shiffrin and Schneider, 1977). The idea is usually expressed in the context of a single-capacity theory of attention such as Kahneman's (1973) or Posner and Boies' (1971). In such theories attentional capacity is thought to *energize* performance, and the amount of capacity allocated to a process determines the amount or rate of processing. Processes can vary in the amount of capacity they require, and automatic processes are assumed to require no capacity. Somehow capacity demands diminish with practice, though none of these theories provides an explicit learning mechanism.

The modal view provides a clear answer to the first question about why automatic processes have the properties they do. Automatic processes are fast because they are not limited by the amount of available capacity. They are effortless because effort is proportional to the amount of capacity allocated to the process. Automatic processes require no capacity; therefore, they require no effort. Automatic processing is autonomous or obligatory because attentional control is exerted by allocating capacity, and a process that does not require capacity cannot be controlled by allocating capacity. It will be triggered whenever the appropriate stimuli appear, whether or not capacity is allocated to it. Automatic processing is also unconscious because attention is the mechanism of consciousness, and we are conscious only of those things to which we pay attention (allocate capacity; see Posner and Boies, 1971; Posner and Klein, 1973).

The modal view *describes* but does not *explain* the development of automaticity. Many authors argue that the demand for attention diminishes with practice: for example, attention is initially required to support performance by establishing temporary connections between stimuli and responses or by controlling the order in which mental operations are sequenced. Practice somehow strengthens the connections or allows sequential processes to be executed in parallel, so that attention progressively becomes less necessary to support performance and finally is not required at all.

This description fits well with intuition, and many experiments show that attentional effects diminish with practice. Two important examples are the reduction of information load effects in visual- and memory-search tasks (Schneider and Shiffrin, 1977) and the reduction of interference between concurrent tasks (Logan, 1979). But description is not explanation. A serious weakness of the modal view is that no theory specifies how the reduction in demand comes about.

The modal view provides a descriptive—not explanatory—answer to the third question of how the properties of automatic processes develop with practice. The properties develop because they are characteristic of processes that require little or no capacity, and capacity demands diminish with practice.

The modal view also has difficulty dealing with the importance of consistency, as it assumes that automatization makes the process underlying performance faster and more efficient. Such *process-based* learning depends on the number of times the process is exercised, regardless of the stimuli exercised with. For example, in a flat city like Champaign, Illinois, the effect of jogging on cardiovascular fitness depends on the distance jogged and not the route chosen. Thus process-based learning predicts no effect (or weak effects) of consistency, contrary to the facts.

By the late 1970s, the modal view had a stronghold on the ivory tower. It seemed able to accommodate the facts of automaticity, and its underlying single-capacity theory seemed able to account for most of the facts about attention (see, for example, Kahneman, 1973). But then *multiple-resource* theory arose to challenge the single-capacity view of divided attention and dual-task performance arguing that more than one capacity or resource limited performance (Navon and Gopher, 1979; Wickens, 1980, 1984). There was abundant evidence that interference depended on the modality of input, output, and central processing rather than on the total amount of information to be processed (see Wickens, 1980), so multiple-resource theory won a quick victory. Adherents of the single-capacity view admitted the existence of multiple resources but argued that one resource—an executive resource associated with attentional capacity—dominated the rest (e.g., Logan, 1979).

Multiple-resource theories were directed primarily at dual-task and divided-attention situations and never dealt seriously with automaticity. Those that broached the issue often reiterated the modal view—that automatic processes use fewer resources (e.g., Navon and Gopher, 1979; Wickens, 1984). But the meaning of this claim is not as clear in multiple-resource theories as it was in the single-capacity theories that inspired the modal view. In multiple-resource theories it is not clear *which* resources an automatic process should use fewer of. One possibility is that automatic processes use less of some particular single resource. Some theorists have argued for an executive resource that is used in all tasks (e.g., Logan, 1979); automatic processes would use less of that resource. But it is not clear whether any single resource acts as an executive or whether the executive uses only one resource. Logan, Zbrodoff, and Fostey (1983), for example, argued that executive processing uses several resources.

Another possibility is that automatic processes use fewer of whatever resources the task used to begin with. Performance becomes more efficient—that is, cheaper—with practice. But there is no easy way to differentiate this alternative from the possibility that practice changes the resource composition of a task by shifting from one set of resources to another (e.g., West, 1967). Performance will appear more efficient with respect to the resources relied on initially but *less* efficient with respect to the resources relied on after practice. Automaticity will have *increased* the amount of those resources required, and this is difficult to reconcile with the modal view that automatic processing is efficient.

One could salvage the modal view by arguing that the total amount of resources used was less after practice than before, but this creates a serious measurement problem that no theory is yet equipped to solve: How can the different resources be made commensurate? How many units of one resource equal a unit of another? Without an answer to these questions, one cannot compare the amount of resources used before and after a shift in resource composition or evaluate the claim that automatic processes use fewer resources. The bottom line is that multiple-resource theories raise difficult problems for resource-based theories of automaticity.

To make matters worse, serious attacks have been made on the idea of resources and the economic metaphor on which it is based (e.g., Allport, 1980; Navon, 1984; Neisser, 1976). Some researchers challenge the idea that performance is limited by entities or energies that can be used by only one process, and that entities or energies released by one process can be used by another (Navon, 1984). Others argue against a resource interpretation of the modality effects that defeated the single-capacity view, suggesting other mechanisms of interference such as noise and crosstalk (Navon and Miller, 1987).

These issues represent internal conflicts in the resource theory camp that remain to be resolved. They may be the death knell for resource theories or may only be difficult stages in a healthy development. Only time will tell. But they do represent serious problems for the modal view of automaticity: if resource theory dies, the modal view loses the core assumption—single capacity—that provided theoretical coherence to the concept of automaticity. If resource theory is to survive, the modal view must grapple with the problems of multiple resources. Clearly the dominant force in the ivory tower is under duress, ripe for a revolution.

Antithesis: Automaticity and Memory

The revolutionary view is that automaticity is a memory phenomenon. Performance is considered automatic when it depends on single-step, direct-access retrieval of solutions from memory rather than on some sort of algorithmic computation. For example, a person familiar with the spatial layout of a town navigates automatically, in that the goal and the current features of the landscape retrieve a travel plan or a direction from memory. A person unfamiliar with the town could not navigate automatically, as he or she would have nothing to retrieve from memory and so would have to depend on general map reading skills, and close attention to road signs to reach his or her destination.

This idea is both old and new. It was at the core of Bryan and Harter's (1897, 1899) analysis of the acquisition of telegraphy skill and it is the essence of several current theories of skill acquisition and automatization (e.g., Logan, 1988; Newell and Rosenbloom, 1981; Rosenbloom and Newell, 1986; Schneider, 1985). It appears in various guises in the literature. Though theories differ in their assumptions about internal processes and representations and the role of resources, they all assume (implicitly or explicitly) that automatization reflects the build-up of information in memory.

The challenge to the resource view lies in the possibility, expressed in the more radical theories (Logan, 1988; Newell and Rosenbloom, 1981), that resources play no role in automatization. These theories propose that novice performance is limited by a lack of knowledge rather than by a lack of resources. Through practice with specific problems novices learn specific solutions, which they can apply when faced again with the same problem or generalize when faced with a similar problem. At some point they will have learned enough to be able to retrieve solutions for all or most of the problems encountered in the domain: they will have achieved the automaticity associated with expertise.

The automaticity-as-memory view provides clear answers to the four general questions raised at the beginning of the paper. First, automatic processes have certain properties because those properties are characteristic of memory retrieval. Automatic processing is fast, effortless, and unconscious because the conditions that prevail in studies of automaticity (i.e., extensive practice) are good for memory retrieval. The memory traces that support automatic processing are "strong" in some sense, which allows them to be retrieved rapidly (hence the speed) and reliably (hence the effortlessness) in a single step. Single-step retrieval would seem unconscious because there are no intervening steps or stages upon which to introspect. Automatic processing is obligatory because memory retrieval is obligatory; attention to an object is sufficient to cause retrieval of whatever information has been associated with it in the past (Keele, 1973; Logan, 1988; also see Kahneman and Treisman, 1984).

Second, the automaticity-as-memory view provides several mechanisms by which automaticity can be acquired. The most common mechanism is *strengthening*, in which a connection between a stimulus and a response (or the like) becomes progressively stronger with practice (e.g., LaBerge and Samuels, 1974; Schneider, 1985; Shiffrin and Schneider, 1977). Another common mechanism is *table look-up*, in which specific responses to specific input patterns are learned and held in a table that is consulted whenever another input appears. If the input matches a pattern in the table, the associated response is executed; if not, some other procedure is carried out to compute the response (e.g., Newell and Rosenbloom, 1981; Rosenbloom and Newell, 1986). A third mechanism is *instance learning*, in which each encounter with a stimulus is represented separately in memory, and multiple exposures to the same stimulus result in multiple representations of that stimulus in memory. These representations are retrieved when the stimulus (or one like it) is encountered again; the more practice, the more representations, and thus the greater the impact on retrieval (i.e., the faster and more reliable the retrieval; see Landauer, 1975; Logan, 1988).

Third, the memory view accounts for the emergence of the properties of automaticity with practice. The general principle is that the properties of memory retrieval may be very different from the properties of the algorithms on which novices rely. Early in practice, performance will reflect the properties of the algorithm, whereas later it will reflect the properties of memory retrieval. The properties of memory retrieval will "emerge" from the properties of the algorithm as subjects switch from one to the other. Because no theory as yet makes specific predictions about when specific properties emerge, the account at present is more descriptive than explanatory.

Fourth, consistency is very important in the automaticity-as-memory view. It assumes that subjects learn specific responses to specific stimuli, and that with such *item-based* learning, transfer to new stimuli should be poor. Changing the mapping rules should also impair performance because the old responses retrieved from memory are no longer relevant. Thus automaticity-as-memory accounts easily for consistency effects.

The automaticity-as-memory interpretation appears to provide a better account of the basic phenomena of automaticity than does the modal resource view. But there are other questions to be answered. The most difficult problem is why novice performance is so poor. The stock answer is that it is unskilled: skilled performance is good, so unskilled performance must be poor. But this is not an explanation. The difficulties experienced by novices reflect deep principles of mental functioning that must be elucidated. Why do novices find certain things difficult and others things easy? Resource theories provide a ready answer, but the automaticity-as-memory view has little to say (but see Anderson, 1982; Schneider, 1985).

Synthesis: Points of Compatibility and Compromise

At this point we may speculate on the outcome of the battle and consider the consequences. It seems certain that the automaticity-as-memory view will capture important ground in the academic arena. The question is whether it will drive out resource theories or coalesce with them to form a composite theory of learning and performance.

It is hard to say whether automaticity-as-memory will entirely replace the modal view; it depends in part on the resource theorists, their interest in the phenomena of automaticity, and their cleverness and tenacity in solving the problems raised previously. However, there is nothing in the automaticity-as-memory view that *necessitates* the idea of resources. Memory theories typically do not invoke the concept of resources, and one can envision a relatively complete theory of performance without it, as evidenced by Anderson's (1982, 1983) work. So the automaticity-as-memory view is not likely to be challenged by attacks on resource theory but will remain strong and ready to replace the modal view if resource theory dies.

But if resource theory survives, can it be integrated with memory theory? Possibly. The strengths and weaknesses of resource and memory theories seem complementary: resource theory is strong on explaining novice performance and weak on learning, whereas automaticity-as-memory is the opposite. There appears to be no basic incompatibility between resource theory and memory theory. Even though there have been few points of contact in the literature, there is no reason in principle why performance could not be described both in terms of resources and memory. A new theory would have to be developed, but the building blocks have been identified.

In the new theory, reduction of resource demands could be a cause or a consequence of automatization. For example, one could adapt Crossman's (1959) learning theory to make resource reduction a causal factor. Crossman argued for a kind of "natural selection" process in which methods were selected randomly; if they were faster than average, the probability of their being selected again was increased. Over practice, the fastest method comes to dominate. The same sort of process could work with resource demands rather than speed as the criterion: methods could be selected randomly, and if they demanded less capacity than average, their selection probability would increase. Eventually, the least demanding method would dominate. In the meantime, resource demands would decrease gradually with practice.

Alternatively, in Logan's (1988) memory-instance theory, resource reduction could be seen as a consequence of automatization rather than a cause. The single-step, direct-access retrieval of a solution from memory that Logan characterizes as automaticity could involve few resources compared with the demands of the multistep algorithms that govern novice or intermediate performance. Automatic performance is simpler than novice performance and so would demand fewer resources. However, automatization is a consequence of experience, not a consequence of a need to reduce resource demands. Logan assumes that encoding into memory and retrieval from memory are obligatory consequences of attention. Attending to an object causes it to be encoded into memory and at the same time makes available whatever was associated with that object in the past. Practice forces a person to attend to aspects of the task, which are obligatorily encoded into memory. Repeated exposure adds more to memory, and the more there is in memory, the faster and more reliable the retrieval. Performance becomes fast and effortless. Resource requirements (if any) would diminish as single-step retrieval comes to dominate performance. However, the reduction in demand would be a consequence of automatization, not a cause or a motivation for it.

Whether resource reduction is a cause or a consequence of automatization, memory will be important in the new theory. Even if resource theory dies and the modal view of automaticity dies with it, memory and the theoretical and empirical principles that govern it will have important implications for automaticity. In the remaining sections I will outline some of these implications.

IMPLICATIONS OF AUTOMATICITY-AS-MEMORY

Somewhere, beyond the shadow of the ivory tower, it may not seem to matter much in a practical sense whether automaticity is a resource phenomenon or a memory phenomenon. Many battles have raged in the ivory tower with no effect in the practical world, and this may be another. I would argue the contrary, for the issue is fundamental. The different approaches provide vastly different perspectives on automaticity, and what was difficult to see from one perspective can become obvious from the other. The new perspective may be illuminating for theorist and practitioner alike. This paper so far has demonstrated that the memory view has gained significant ground and can no longer be ignored. Whether or not we abandon the old (resource) perspective, we must give serious attention to the new one and see what insights it provides.

The disparity of perspective is most apparent on the issue of what is learned. The modal resource view argues that people learn about the processes underlying their behavior, becoming faster and more efficient with practice (e.g., Anderson, 1982; Kolers, 1975). The memory view argues that people learn about the environment in which they perform, remembering behaviors appropriate to the different states of the environment (e.g., Logan, 1988; Newell and Rosenbloom, 1981). These views raise different questions about training. The modal view leads one to ask about the resource demands of the situation and ways to reduce resource demands. The memory view leads to questions about what must be learned to perform the task and ways to improve that learning.

In general, the two perspectives predict different gradients of transfer of automaticity. The modal view predicts broader transfer than the memory view because learning is process-based and the specific stimuli do not matter. The memory view predicts narrower transfer because only specific responses to specific stimuli are available in memory. These predictions have important practical implications for the design of training programs: anticipating narrow transfer, the memory view would emphasize fidelity in training programs and simulators so that situations encountered in training were as similar as possible to situations encountered in the field when training is applied. For the same reason, the memory view would emphasize breadth of training, so that the situations encountered in training were representative of those in the field. Neither fidelity nor representativeness would be particularly important in the modal view, provided that resource demands do not change much from training to application.

There is a an extensive literature on the psychology of memory that can provide answers to questions about automaticity. Its relevance, hidden or disguised from the modal perspective, is immediately recognizable from the memory perspective wherein some factors take on new meaning and other factors become apparent for the first time. Levels of processing is an example of the former. It was viewed as a difficulty manipulation in the resource view, with deeper levels demanding more resources (e.g., Johnston and Heinz, 1978). But from the memory perspective, levels of processing affect memorability, with better memory for deeper processing (e.g., Craik and Tulving, 1975). The better memory may also facilitate automatization.

Other factors, not readily apparent in the modal view, may have powerful effects on memory and thus on automatization. Context and the match between conditions of encoding and retrieval are important examples (e.g., Eich, 1980; Tulving and Thompson, 1973) with particular relevance to automatization. These factors will be explored in the remainder of the paper.

Context Effects

Context can have powerful effects on memory. One of the most dramatic demonstrations of its power was Godden and Baddeley's (1975) experiment with deep-sea divers. Once under water, divers apparently forget instructions they had been given on the surface and Godden and Baddeley discovered why. They had divers learn materials on the surface and tested them either underwater or on the surface. They found better memory on the surface than underwater, replicating the anecdotal reports. However, divers who learned the same materials underwater showed better memory underwater than on the surface, suggesting that the match between context at encoding and context at retrieval was the crucial variable.

Similar context effects have been produced by less drastic manipulations (for reviews, see Eich, 1980; Tulving and Thompson, 1973), though the effects are usually smaller in magnitude. Some context manipulations, such as the room in which the items were encoded and retrieved, have very little effect (Eich, 1985). Others, such as the location in which an item appears, can have strong effects (Winograd and Church, 1988). In general these effects are explained by assuming that the context at encoding is associated with the item in the memory trace and that context at retrieval is an important retrieval cue. The difficulty of retrieval depends on the match between the retrieval cues and the memory trace, and the match will be better when encoding and retrieval contexts are the same than when they differ. Thus similar contexts produce better memory performance than dissimilar ones (Metcalfe, 1985; Tulving and Thompson, 1973).

If automaticity is a memory phenomenon, governed by the theoretical and empirical principles that govern memory, then context effects should be important to automaticity and automatization. There is no published research on context effects in automaticity, so the question remains open. However, one can make some tentative predictions.

In most learning mechanisms, common features become progressively stronger with experience and unique features are buried more deeply in noise. In Logan's (1988) theory, for example, experiences are stored separately and amalgamated at retrieval. When there is only a single experience in memory, its common and unique features should be (roughly) equally retrievable. As other experiences are added, unique features become harder to retrieve. The unique features of one experience act as noise with respect to the unique features of other experiences, and the more experiences there are, the greater the amount of noise, hence the more difficult the retrieval. By definition, common features are present in nearly every experience. The common features of one experience reinforce the common features of other experiences, so they remain strong relative to the noise and easily retrievable. Other theories make similar predictions (e.g., Metcalfe, 1985; Schneider, 1985).

This analysis suggests that context effects will be more important early in practice, when unique features are easily retrieved, than later in practice, when unique features are hard to retrieve. Thus the impact of context in practical situations may depend on the amount of practice involved. At very high levels of practice context effects may be safely ignored, but at lower levels of practice or at mixtures of high and low levels some attention should be paid to context effects.

The consistency of the context is also an important consideration. Context is encoded and retrieved just as task-relevant information is encoded and retrieved, and contextual consistencies should be strengthened with practice just as task-relevant consistencies are. Contextual consistencies may come to be associated with task-relevant consistencies, locking the ability to perform the task into a specific context. Different contexts may inhibit retrieval of task-relevant information. It may be possible to immunize the learner against these effects by training in different (i.e., inconsistent) contexts so that no contextual features become uniquely associated with task-relevant features. Context would contribute noise to retrieval but would not bias it, locking out task-relevant information.

Contextual consistency can have facilitating effects if the context at application matches the context of training. In practice, application may differ from training considerably, but there may be aspects of the context that remain consistent. For example, a given procedure may always be executed in the context of a certain goal or a certain class of goals though the goals are sought in different situations. Consistency of goals may facilitate retrieval of task-relevant information even in the face of different situational contexts.

The practitioner may have little control over context at application, which is often determined by other factors such as the mission to be accomplished and the equipment to be used. However, he or she can control the context at training and should design it to take into account the breadth and nature of the context at application. Broad contexts at training may lead to better transfer but are likely to be more expensive than narrower contexts and may not be worth the extra expense if the application context is narrow. Another possibility for the practitioner is to discourage or prevent attention to context during training so that context does not become associated with task-relevant information in the memory trace. There will then be no interference from mismatching context at application (though there will also be no benefit from matching context).

Dual-Task Conditions as Context

The concurrent task in dual-task conditions may be interpreted as a context for the primary task, and some of the difficulty involved in performing and learning dual tasks may be attributed to context effects. A task may be viewed as a stream of events that become associated as the subject attends to them. Two tasks performed together present concurrent streams of events, and it is possible that events from one stream become associated with the other. But if the tasks are really separate, then the streams of events that comprise them will tend toward independence and associations between streams will be spurious. When an event occurs again in one stream, it is unlikely that the simultaneous event from the other stream that occurred with it will occur with it once again. The contextual associations will not match, and retrieval will be less effective; consequently, performance will seem less automatic than it could be.

To make the point concretely, imagine two concurrent categorization tasks, one in which subjects search for names of Mexican restaurants (e.g., Casa Lupita) and one in which they search for birthdates of Canadian psychologists (e.g., the present author). Imagine that there are 10 restaurant names and 10 psychologists. In single-task conditions learning is relatively simple: there are 20 associations to learn. But in properly balanced dual-task conditions each restaurant would be paired with each psychologist, so there would be 100 associations to learn. To make matters worse, dual-task associations would recur less frequently than single-task associations: in the 100 trials required to present each dual-task pair once, each single-task stimulus could be presented five times. Dual-task conditions present less opportunity to show evidence of learning.

There is no direct evidence on the importance of context in dual-task performance. There is, however, evidence that dual-task conditions impair memory (Fisk and Schneider, 1984) and inhibit learning (Nissen and Bullemer, 1987), which is consistent with the idea of mismatching context. The modality effects in dual-task performance (Wickens, 1980) are also consistent with the idea of mismatching context: subjects may be more likely to associate events from the two streams if the tasks involve the same modality than if they involve different modalities. Thus context effects would be stronger within modality than between modality.

The dual-tasks-as-context hypothesis predicts more specific modality effects than the multiple-resources view. Not only does the modality matter, but the materials within the modality matter as well. The context hypothesis thus has an easier time than resource theory in dealing with Hirst and Kalmar's (1987) results. Hirst and Kalmar found more interference when subjects performed two concurrent searches for members of the same category than when they performed two concurrent searches for members of different categories. To account for these results, a resource theory would have to argue that each category was a separate resource. The context hypothesis would merely have to argue that each category was represented separately in memory, a proposition for which there is a lot of independent evidence (Medin and Smith, 1984).

The context hypothesis may also explain why training does not appear to produce immunity to dual-task interference. A number of studies show substantial interference when a dual task is introduced, even when subjects have been trained to some criterion of automaticity (Logan, 1979; Schneider and Fisk, 1984; Smith and Lerner, 1986). Single-task training may reduce dual-task interference but apparently does not eliminate it (Bahrick, Noble, and Fitts, 1954). The context hypothesis would interpret these results in terms of a shift in retrieval cues: the stimuli from the added task work together with the stimuli from the trained task as compound retrieval cues, and there is less available to the compound cue than there would be to the well-trained single-task cue. Consequently memory is slower and less reliable and performance is less automatic.

The message for the practitioner is to pay attention to the tasks that will be performed concurrently with the task one is training. One should try to incorporate into training concurrent tasks similar to those anticipated in application so that the trainees will have had experience with the appropriate context. Also, training programs should encourage trainees to treat the two tasks separately—to ignore the context provided by the other task so as not to incorporate it into memory traces relevant to the primary task. Perhaps training under a variety of dual-task conditions would encourage inattention to context and develop immunity to interference from new dual tasks at application.

Levels-of-Processing Effects

Level of processing is a potent variable in memory research. By manipulating subjects' orienting task, experimenters require them to attend to different properties of the stimulus. In general, subjects who attend to low-level physical features do not remember the materials as well as subjects who attend to higher-level semantic features (Craik and Tulving, 1975). The effect is well established and easily replicable, though not understood theoretically. Some hypotheses have been advanced (e.g., deeper processing is more distinctive or more elaborate), but as yet no one has discovered a way to define depth independent of memory performance. This inherent circularity has led memory researchers to lose interest in the phenomenon in recent years; but at an empirical level it is robust and important.

If automaticity is a memory phenomenon, then levels of processing might have the same effect on automatization as it does on "standard" measures of memory such as recognition and recall—we might expect faster learning and better retention the deeper the level of processing. Logan (1985b) reported experiments consistent with this hypothesis. He presented pairs of words and had subjects make category or rhyme judgments about them (e.g., is *professor* a *profession?* does *sleigh* rhyme with *play?*). On the initial presentation, reaction times were the same for the two judgments. But on the second presentation, reaction times were much faster for the category judgments than for the rhyme judgments, as if subjects had learned more. It remains to be seen whether this initial advantage for deeper processing would persist throughout practice and produce a faster learning rate, but the results are suggestive.

There is some indication that levels-of-processing effects may not generalize to memory as reflected in studies of automaticity. Jacoby and Dallas (1981) exposed subjects to words under orienting tasks that varied in level of processing and then transferred the subjects to standard memory tests (recognition and recall) or to a perceptual identification task, in which the words were exposed briefly and subjects were to identify them. The standard levels-of-processing effects were replicated in recognition and recall but not in perceptual identification. Words presented during the orienting task were identified more accurately than words not presented before (indicating the presence of the former in memory), but the advantage was no greater for deep orienting tasks than for shallow ones. If the memory processes that underlie automaticity are the same as those that underlie perceptual identification, then these results suggest that levels of processing may have no impact on automatization. But if automatic memory processes are similar to those that underlie the repetition effect that Logan (1985b) studied, then there is reason to be encouraged. At present the question seems relatively open and promises to be a fertile ground for future research.

The results thus far, although speculative, may have some implications for the practitioner. They suggest that training may be more effective if it involves a deeper level of processing—that is, if trainees can become involved in the training task in a meaningful way. The more commitment and interest they show in the training program, the faster they may learn and the better they may retain what they learn in applying their knowledge once training is over.

The implications of levels of processing are less clear than the implications of context because the former variable is less well understood theoretically than the latter. Implications of context can be deduced from the various theoretical mechanisms proposed to account for context effects, whereas the implications of levels of processing must be induced from empirical observations. Deduction is better than induction, if one's premises are true, so there is more to be said about context effects than about levels of processing. This contrast illustrates once again that theoretical disputes can have important practical implications. As Barry Kantowitz once said, there is nothing so practical as a good theory.

Implicit and Explicit Memory

The contrast between Logan's (1985b) findings and those of Jacoby and Dallas (1981) points to an important distinction in the memory literature that is currently the focus of a hot debate: the distinction between *implicit* and *explicit* memory (for reviews, see Jacoby and Brooks, 1984; Schacter, 1987; Tulving, 1983). The distinction addresses the nature of the retrieval task used to probe memory. In explicit memory tasks such as recognition and recall, the subject is explicitly told to retrieve something from memory (e.g., the words that appeared on a previous list or the context associated with a currently presented item). The subject understands it as a memory task and consciously tries to use memory. In implicit memory tasks, the subject is given a task to perform of which some of the materials have been presented before. The experimenter infers memory for those materials if the subject performs better on them than on comparable materials that were not presented before. The requirement to use memory is implicit in the instruction to perform the same task on familiar materials, but there is no explicit instruction to use memory. The subject may not understand the task as a memory task and may not consciously try to use memory.

At a procedural level, the distinction amounts to a contrast between retrieval tasks: recognition and recall versus all the others. But some theorists have argued for a deeper distinction, contending that the tasks tap different memory systems (e.g., Tulving, 1983). Others agree that the distinction is deep but argue that the tasks tap the same memory system in different ways (e.g., Jacoby and Brooks, 1984). The debate is fueled by a provocative and important data base in the form of dissociations between the different measures of memory. There are several indications that factors affecting explicit memory have no effect or a different effect on implicit memory. Jacoby and Dallas's (1981) results on levels-of-processing effects in recognition versus perceptual identification are an example of the dissociation. Perhaps the most compelling dissociations come from amnesic patients, who show evidence of learning on problem-solving tasks even though they cannot recall having performed the task before (e.g., Cohen and Squire, 1980). However, dissociations are not always found. In some cases there are associations; for example, in Logan's (1985b) levels-of-processing experiments. And there is some debate over the interpretation of dissociations (see Dunn and Kirsner, 1988).

The explicit/implicit memory issue is another battle raging in the ivory tower. The debate may have strong implications for the role of memory in automaticity because automaticity seems more likely to be a phenomenon of implicit memory than of explicit memory. But it is too early to tell. The theoretical alternatives need to be worked out in more detail before they can be rigorously tested, and the relation between these memory effects and automaticity needs to be spelled out. Dissociation experiments typically use only one presentation, whereas automaticity experiments can involve thousands. The data sets may represent different points on the same acquisition curve, and effects at any one point may generalize to any other. But from some perspectives, different factors affect different parts of the learning curve. In Logan's (1988) theory, for example, performance depends on a race between memory retrieval and a general algorithm for performing the task. At low levels of practice memory retrieval is slow and unreliable, so performance is dominated by the algorithm. At high levels memory retrieval is fast and accurate and dominates performance. Thus the first exposure or two investigated in studies of implicit and explicit memory may reflect properties of the algorithm more than properties of memory. Consequently, the results may not generalize to higher levels of practice when performance is based entirely on memory retrieval.

In addition, the two kinds of memory may not be as mutually exclusive as the distinction suggests. There is no reason why someone may not try to use memory consciously or explicitly while performing an implicit memory task. Stuart Klapp and I performed some experiments that suggest that the distinction may be blurred when applied to automaticity. We trained people on an alphabet arithmetic task in which they were presented with equations to verify, such as $A + 2 = C$ or $B + 3 = E$. In essence, we were asking whether C was two letters down the alphabet from A, whether E was three letters down from B, and so on. Initially, subjects reported performing the task by counting through the alphabet for a number of steps determined by the digit addend and then comparing the counted letter with the presented one. Consistent with subjects' reports, verification times increased linearly with the magnitude of the digit addend with a slope of between 400 and 500 ms/count. With practice, however, subjects reported remembering specific problems, and the slope diminished to zero. Performance had become automatic.

We were able to reproduce this automaticity by having subjects learn the facts by rote memory, without counting. When transferred to a verification task that used the facts they had learned, subjects showed a zero slope, suggesting automaticity. But when subjects were transferred to verify unfamiliar facts, their slopes were around 400 ms/count—as were those of other untrained subjects. In subsequent experiments we compared learning by rote with learning by doing and found very little difference. Basically, the slope in the verification task depends on the number of prior exposures to the facts in question, regardless of whether the exposures occurred in a verification task (learning by doing) or in a memory task (learning by rote). We are currently trying to test the limits of this effect (or lack of effect) and to generalize the findings to other criteria for automaticity, such as immunity to dual-task interference. For now, the results are provocative in that they suggest that training under implicit and explicit memory conditions may have equivalent effects on automatization.

The moral of the story for practitioners is to keep an eye on the debate over explicit and implicit memory. It is too early to tell the outcome, but it may have profound implications for theories of automaticity and the training programs that apply them.

Procedural and Declarative Knowledge: Automaticity as Motor Skill

Automaticity often seems to be on one side of another distinction related to the explicit/implicit memory debate and important in cognition in general: the distinction between *declarative* and *procedural* knowledge. Declarative knowledge is knowledge of facts, "knowing that" something is the case; whereas procedural knowledge is knowledge of process, "knowing how" to do something. Automaticity is often characterized as procedural knowledge. A common interpretation is that skill acquisition reflects a transition from declarative knowledge to procedural knowledge (e.g., Anderson, 1982). This view is buttressed by the tendency to use perceptual-motor skills, such as riding a bicycle, as paradigm cases of automaticity. Perceptual-motor skills appear to be both automatic and procedural, so the shoe would seem to fit.

However, the fact that some perceptual-motor skills are automatic and some procedural skills are automatic does not imply that all automatic skills are procedural or perceptual-motor. There is no reason why declarative knowledge or cognitive skills cannot be automatized. My experiments with Klapp, described previously, suggest that declarative knowledge (acquired when learning by rote) can be used to support automatic performance. More generally, Logan's (1988) theory argues that automaticity results from building up memory traces regardless of whether the traces represent procedural or declarative knowledge. There may be few studies of automaticity based on declarative knowledge in the literature, but this may reflect an absence of curiosity about the topic rather than an absence of phenomena to study.

The moral for the practitioner here is to look more broadly for automatic processes. They need not be restricted to procedural knowledge or perceptual-motor skill but may permeate the most intellectual activities in the application environment. For example, common lore and the modal view might lead one to expect that pilots should be able to automatize the perceptual and motor aspects of flying. The memory view suggests that they may also be able to automatize some of the strategic and intellective aspects of carrying out their mission.

SUMMARY AND CONCLUSIONS

There is a battle raging in the ivory tower over the concept of automaticity. The defenders of the established view—adherents of resource theories of automaticity—have suffered serious losses through both a frontal attack from proponents of the memory view of automaticity and a flank attack from enemies of resource theory in general. The memory view seems to have gained a solid foothold and consequently will influence the field for some time to come. One purpose of this paper has been to argue that practitioners should take an interest in the battle because the outcome thus far has strong implications for the design of training programs and for the understanding of expertise.

The memory view provides a new perspective on issues in automaticity and training that was not available from the modal resource view, just as one eye provides a perspective not available to the other. Ivory tower theorists may build their careers by arguing about which eye provides the better view. The wise practitioner will look with both eyes open and enjoy the benefits of binocular vision.

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