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Attention and automaticity: Toward a theoretical integration

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Abstract We sketch an initial version of a theory intended to account for the role of attention in the acquisition and expression of automaticity, and we test some initial predictions. The theory combines Logan's instance theory of automaticity and Bundesen's theory of visual attention, with Bundesen's theory determining what Logan's theory learns. We report four experiments that test the assumption that subjects learn what they report explicitly do not learn what they do not report explicitly. The experiments provide partial support for the predictions and encourage further development of the combined theory.

Introduction

Researchers have debated the relation between attention and automaticity since the beginning of the cognitive revolution. From 1950 to 1980, approximately, most researchers thought attention was independent of automatic processing. In the 1950s and 1960s, the dominant paradigm was selective attention, and research focused on the fate of unattended material. Theorists distinguished between preattentive processes, which were parallel and unlimited in capacity (hence, automatic), and attentive processes, which were serial and limited in capacity (e.g., Broadbent 1958; Deutsch & Deutsch, 1963; Norman, 1968). Researchers disagreed on the automaticity of perceptual and semantic analysis. Early selection theorists argued that only low-level perceptual features were processed automatically, and semantic access demanded attention (e.g., Broadbent, 1958). Late selection theorists argued that all features, from perceptual to semantic, were processed automatically, and attention was required only to select responses (e.g., Deutsch & Deutsch, 1963; Norman, 1968). They all assumed that automatic processes were separate from and independent of attention. The question was, where was the boundary between them?

In the 1970s, the dominant paradigm shifted from selective to divided attention, and the idea that automaticity was learned became a focal topic. Many theorists claimed that automatic processing was independent of attention by definition (e.g., LaBerge & Samuels, 1974; Shiffrin & Schneider, 1977). The acquisition of automaticity was described as a gradual withdrawal of attention over practice (e.g., LaBerge & Samuels, 1974; Shiffrin & Schneider, 1977). Again, automatic processing was separate from and independent of attention.

Since the 1980s, researchers have increasingly challenged the assumption that attention and automatic processing are independent, demonstrating strong interactions between attention and automaticity in several paradigms. Some researchers showed that attention modulated Stroop interference (e.g., Kahneman & Chajzyck, 1983; Kahneman & Henik, 1981; Logan, 1980) and semantic priming (Smith, 1979; Smith, Theodore, & Franklin, 1983), which were paradigm cases of automaticity. Others showed top-down, attentional influences on preattentive processing (e.g., Cave & Wolfe, 1990; Wolfe, Cave, & Franzel, 1989), which earlier researchers had thought were independent. Still others examined the role of attention in acquiring automaticity and found strong interactions. Attention determines what is learned in training and what is expressed in skilled performance (e.g., Boronat & Logan, 1997; Haider & Frensch, 1996; Logan & Etherton, 1994; Stadler, 1995).

The relation between attention and automaticity is not yet resolved. Some theorists argue for strong dependence (e.g., Logan 1988), while others argue for independence by definition (e.g., Jacoby, 1991). It may not be possible, at present, to resolve the issue in a general way that applies to all theories (and convinces all theorists). A better strategy may be to address the issue

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specifically, in the context of a particular theory of attention and automaticity, as Schneider did (Schneider, 1985; Schneider & Detweiler, 1987). Our purpose in this article is to take some steps toward that goal, proposing a theory that tries to explain both attention and automaticity and account for the role of attention in automatization. Our specific goal is to integrate two theories in which attention and automaticity already interact strongly: Logan's (1988, 1990) *instance theory of automaticity* and Bundesen's (1990) *theory of visual attention*. In this article, we describe points of compatibility between the two theories, and we report experiments that test predictions about what is learned during automatization that are drawn from an interpretation of Bundesen's (1990) theory.

The instance theory of automaticity

The instance theory assumes that automatic processing is based on single-step direct-access retrieval of prior solutions from memory. Novice performance is based on some kind of algorithmic computation. With practice, over the course of automatization, the algorithm drops out and memory retrieval takes over. Automatization is a transition from algorithm-based performance to memory-based performance.

The instance theory rests on three main assumptions: *obligatory encoding*, *obligatory retrieval*, and *instance representation* (Logan, 1988, 1990). The obligatory encoding assumption states that encoding into long-term memory is a necessary consequence of attention. Whatever is attended is encoded into memory. The encoding may not be perfect, depending on the stimulus conditions and the constraints on attention, but the point is that nothing beyond attending is required to store a trace in memory. The obligatory retrieval assumption states that retrieval from long-term memory is a necessary consequence of attention. Whatever is attended acts as a retrieval cue that pulls things associated with it from memory. The retrieval cue may not be very effective, depending on stimulus conditions, constraints on attention, and the state of long-term memory, but nothing beyond attending is required to initiate retrieval. The instance representation assumption states that each encounter with a stimulus is encoded, stored, and retrieved separately, even if the stimulus has been encountered before.

These assumptions imply a mechanism by which automaticity develops when subjects practice the same task in the same task environment. According to the obligatory encoding assumption, repeated exposure to the task environment will cause a build-up of traces in memory, forming a task-specific knowledge base. According to the obligatory retrieval assumption, these traces will become available when familiar stimuli are encountered again, and the response from memory will be stronger the more traces there are in memory. Eventually, the response from memory will be strong enough for subjects to abandon the initial algorithm, basing their performance entirely on memory retrieval.

The instance theory provides a formal account of the power-function learning curve that is typically observed in studies of skill acquisition and automatization (Newell & Rosenbloom, 1981). The theory assumes that the different traces in memory race against each other at retrieval time, with performance depending on the first trace (Logan, 1988) or the first few traces (Nosofsky & Palmeri, 1997; Palmeri, 1997) to be retrieved. If performance is based on the first trace to retrieved, it is possible to prove mathematically that the expected retrieval time of the first trace (and thus reaction time) decreases as a power function of the number of traces in memory (and thus, of the number of practice trials; see Logan, 1988, 1992). It performance is based on the first few traces retrieved, then the learning curve approximates a power function (Palmeri, 1997).

The instance theory depends heavily on assumptions about attention. The obligatory encoding assumption and the obligatory retrieval assumption both invoke the concept of attention. In testing the theory so far, we have tried to make general predictions that would hold true for a variety of theories of attention (e.g., Boronat & Logan, 1997; Logan & Etherton, 1994; Logan, Taylor, & Etherton, 1996), but that research strategy can only go so far. Different theories of attention should make different predictions about learning, and the instance theory is incomplete without a specific theory that explains how attention works at encoding and retrieval. The purpose of this article is to investigate the possibility of interfacing the instance theory with Bundesen's (1990) theory of visual attention and recent developments of that theory by Logan (1996) and Logan and Bundesen (1996).

The theory of visual attention

Bundesen's (1990) theory assumes that attentional selection is based on a race between various categorizations of the stimuli in the display. The outcome of the race determines both which stimuli are selected and which interpretations – categorizations – of the stimuli are selected. The theory formalizes the common intuition that stimuli activate representations in memory and that attention modulates the activation, so that the most strongly activated stimuli are selected. The theory goes a step beyond intuition in assuming that activation determines the speed at which processing occurs and that attention modulates processing speed. Thus, the stimulus that activates memory most strongly becomes the stimulus that produces some threshold activation the fastest, and selection becomes a race between alternative categorizations. At the outcome of the race, a representation of the categorization of the selected item is placed in short-term memory, which may be interpreted as a proposition stating that "item x belongs to category i."

In Bundesen's theory, processing rate, which determines attentional selection, depends on three main factors: the quality of the sensory evidence that object x belongs to category i, $\eta(x,i)$ (in essence, the similarity between object x and category i); the bias for categorizing stimuli as members of category i, β_i; and the attentional weight on object x, w_x. The factors combine to produce a processing rate $v(x,i)$ in the following way:

$$v(x, i) = \eta(x, i)\beta_i \frac{w_x}{\sum_{z \in s} W_z} \tag{1}$$

The attentional weight on object x depends on its priority, which is determined by the quality of sensory evidence that x possesses properties relevant to selection. The priority of property j is given by π_j, and the weight given to object x is given by:

$$w_x = \sum_{j \in R} \eta(x, j)\pi_j \tag{2}$$

Bias and priority are set by the subject (i.e., by the subject's homunculus). Quality of sensory evidence depends on the quality of the stimulus and the subject's history of learning. Response probability and latency depend on the processing rates associated with the various stimuli in the display and the categories that are relevant for selection and for report. Details of the predictions for response probability and latency can be found in Bundesen (1990; for the historical development of these ideas, see Bundesen, 1987; Bundesen, Pedersen, & Larsen, 1984; Bundesen, Shibuya, & Larsen, 1985; Logan, 1996; Logan & Bundesen, 1996; Shibuya, 1993; Shibuya & Bundesen, 1988).

Bundesen's (1990) theory depends heavily on the assumption that subjects have learned about category membership in the past. It adopts a particular theory of category representation – *prototype* theory – but it says nothing about how those category representations are acquired. To be complete, the theory needs to specify the learning mechanisms by which category representations are acquired, and the theory of learning and representation needs to account for the vast literature on categorization and concept learning (for a review, see Medin & Smith, 1984). It is clear from this literature that prototype representations are not adequate, so this aspect of the theory must change.

Integrating the instance theory of automaticity and the theory of visual attention

The essential similarity between Logan's (1988, 1990) instance theory and Bundesen's (1990) theory of visual attention is that they both assume that processing depends on a race. In the instance theory, the race looks inward: A stimulus acts as a retrieval cue, causing stored traces to race toward retrieval. In Bundesen's (1990) theory, the race looks outward: Bias and priority cause stimuli to race toward categorization. The key point in integrating the two theories is the idea that the two races may be one and the same. The difference between them may be only a matter of perspective. The traces retrieved in the instance theory may be the categorizations achieved in Bundesen's theory.

The point of contact between the formal versions of the instance theory and Bundesen's (1990) theory of attention is the $\eta(x,i)$ parameters, which reflect the subject's learning history. Bundesen's (1990) theory interprets $\eta(x,i)$ values as similarities between object x and a prototype representing category i. The instance theory takes a different interpretation of category representation, assuming that a category is represented by a collection of exemplars or instances rather than by a summary prototype. According to the instance theory, the relevant similarities are between object x and the N different instances of category i that the subject has experienced in the past. Thus, the instance theory would interpret $\eta(x,i)$ as a summary statistic representing the similarity between object x and all instances of category i experienced in the past. That is,

$$\eta(x, i) = \sum_{k=1}^{N} \eta(x, i_k) \tag{3}$$

The summation of η values for individual instances into an overall η value for the category can be justified by the assumptions of the instance theory and Bundesen's (1990) theory. In the instance theory, the various traces race against each other, and the winner determines performance. The finishing time for the winner of the race can be determined from the distributions of finishing times for the runners. If the distribution for the runners is exponential, then the distribution of the winner's finishing times will also be exponential, with a rate parameter that equals the sum of the rate parameters of the runners in the race. Bundesen's (1990) theory interprets η values as rate parameters for exponential distributions. The finishing time for the winner of the race depends on the sum of the η values in the race. Thus, $\eta(x,i)$ can be interpreted as the finishing time for a single retrieval of the category prototype, as Bundesen (1990) did, or it can be interpreted as the finishing time of a race between N instances. The calculations are the same either way. The theories fit neatly together.

It remains to be seen whether this combination of the formal theories can account quantitatively for learning phenomena and for the interaction of attention and learning. We believe the combination holds promise, because the two theories have been quite successful in past applications in their own domains, and because their race formulations are quite compatible. For the present, however, we focus on a qualitative prediction, which we put to an empirical test.

Testing the combined theory

Encoding of selection and reported attributes

In the combined theory, we assume that encoding into short-term memory is a necessary step in encoding into long-term memory; subjects learn what they encode explicitly in short-term memory. This assumption has many precedents in the memory literature, from Atkinson and Shiffrin (1968) to the present day. The prediction we test follows as a corollary to this assumption: Attributes that are not encoded into short-term memory will not be encoded into long-term memory. We rely on Bundesen's (1990) theory to tell us what will and will not be encoded into short-term memory in a given act of selective attention.

Bundesen's (1990) theory assumes that the result of selection is to place in short-term memory a categorization of the selected stimulus. We interpret the theory as predicting that the categorization depends on the bias parameter, β_i, and not on the priority parameter, π_j. Thus, selection results in a proposition of the form "x is i" in short-term memory. It does not result in a proposition of the form "x is j". Thus, we predict that subjects will learn about the attributes that get high bias parameters, and they will not learn about the attributes that get high priority parameters.

To put this differently, we draw a distinction between *reported* attributes and *selection* attributes, which corresponds roughly to response set and stimulus set, respectively, in the older attention literature (e.g., Broadbent, 1971). The selection attribute specifies which objects are to be selected; the reported attribute specifies what is to be reported about the selected object. Our claim is that subjects have explicit knowledge of the reported attribute of the selected object, but they have no explicit knowledge of the value of the selection attribute. Thus, subjects will learn about reported attributes, but not about selected attributes.

Consider, for example, an experiment in which subjects see two words on a screen, one on top of the other, and their task is to indicate whether one of the words is the member of a target category, such as *metals*. In this experiment, location (top or bottom) is the selection attribute, and metal or non-metal is the reported attribute. Bundesen's (1990) theory would account for subjects' behavior by assuming they set β high for metals and non-metals and π high for top and bottom locations. At the end of a trial, short-term memory would contain the categorization "x is a metal" or "x is not a metal," but no explicit categorization of the position that x occupied. Of course, subjects could infer that x must have occurred in the top position or the bottom position, rather than in some other position, but they would have no way of knowing which one without further processing.

Our prediction, following from our assumption that subjects learn what they represent explicitly in short-term memory, is that subjects would become faster at making decisions about x being a metal over practice, but they would not become faster at processing x's location. If we were to hold x's location constant throughout practice and then change it in transfer, subjects would be insensitive to this change in location.

Consider another example, in which subjects again see two-word displays and must decide whether they contain a member of a target category like *metals*, but this time they must report the location at which the target appears, pressing one key if it appears in the top position and another key if it appears in the bottom position. In this case, location is both a selection attribute and a reported attribute, so we would expect the subjects would learn about location. Bundesen's (1990) theory would assign high β values to metal, non-metal, top-position, and bottom-position, and it would assign high π values to top and bottom locations. At the end of a trial, short-term memory would contain propositions like "x is a metal" and "x is in the top position," which, by our assumption, would then be encoded into long-term memory. If location were held constant throughout training and changed at transfer, subjects should show substantial costs of changing location.

The experiments reported in this article tested these predictions: Subjects should not show costs of changing location at transfer unless they reported location explicitly during training. Put differently, the costs of changing location at transfer, following training in which location was consistent throughout practice, should be greater if subjects reported location explicitly.

Note that our predictions stem from a particular reading of Bundesen's (1990) theory that Bundesen might not share. Bundesen might argue that all attributes of a selected stimulus enter short-term memory. Indeed, a recent paper by Logan and Bundesen (1996), addressed to the bar-probe partial report task, assumed that identities and locations of selected stimuli were placed in short-term memory. However, this is not a necessary prediction from Bundesen's theory. The formal mathematics of the theory address only the probability and latency with which categorizations of the reported attributes enter short-term memory, and that aspect of the theory justifies our interpretation.

Incidental and intentional encoding of location information

Several researchers have examined *explicit memory* for location information, presenting subjects with items in various locations and testing to see whether subjects could recognize or recall the locations the items appeared in. Naveh-Benjamin (1987, 1988), for example, showed that subjects could remember the locations that pictures appeared in, but their memory was better under intentional learning conditions, where they expected to be tested for location information, than under incidental learning conditions, where they had no such expectations. The fact that intentional learning produced better memory than unintentional learning is consistent with our prediction, but the fact that incidental learning produced above-chance recognition and recall does not rest easy with our hypothesis that subjects will learn nothing about location if they do not attend to it explicitly (i.e., if it is not a reported attribute). It is possible, however, that Naveh-Benjamin's subjects attended explicitly to location in both learning condition, and that may save our hypothesis.

Ultimately, our theory should explain explicit memory as well as attention and automaticity. For the present, however, it is focused more on changes in performance with practice, which are known as *implicit memory* in the memory literature (e.g., Roediger, 1990). Thus, performance on tasks that are more like the ones used in the attention and automaticity literature is more germane to our current hypotheses. We know of three examples relevant to our hypothesis.

First, Miller (1988) reported the results of a visual search experiment in which subjects searched for target letters in four-letter displays. One kind of target, the *inducing target*, occurred in one position more often than in any other. Another kind of target, the *test target*, occurred in each position with equal frequency. In several experiments, he found an advantage for targets that occurred in the more frequent position, which suggested that subjects differentially attended that position (i.e., priority was higher for that position). However, the advantage was greater for the inducing target than for the test target, which suggests that subjects associated particular targets with particular positions, contrary to our hypothesis. However, Miller's experiment did not include conditions that required subjects to report location explicitly, so we cannot test our hypothesis that subjects would learn more when they reported location explicitly.

Second, Treisman, Vieira, and Hays (1992) compared search for single features (*feature search*) with search for conjunctions of features (*conjunction search*) using a similar procedure with eight-item displays. In conjunction search, they found large benefits when inducing targets occurred in their usual position and large costs when inducing targets occurred in other positions, but virtually no effect for test targets. In feature search, there was little effect for either inducing or test targets. Treisman et al. interpreted this difference in terms of the attention demands of conjunction and feature search, arguing that conjunction search required attention to location, but feature search did not. The feature search results are consistent with our hypothesis. The conjunction search results are consistent with it if subjects explicitly attended to location and inconsistent with it if they did not. Treisman et al. did not contrast explicit (bias) and implicit (priority) attention to location, so their data do not provide a test of our hypothesis that subjects would learn more when they reported location explicitly.

The third example involves attention to color rather than to location, but the design is similar to our present experiments, so the results are relevant to our current hypotheses. Logan, Taylor, and Etherton (1996) had subjects search two-word displays for a member of a target category. One of the words was white, and the other was red or green. Subjects were told to look at the red or green word and ignore the white one, because the white one would never be a target (i.e., color was a cue to target location). These instructions should set priority high for red and green and low for white. In one experiment, subjects simply reported target presence; in another, subjects reported the color of the target as well as its presence. In both experiments, the colors of particular targets were constant throughout training and changed at transfer. Subjects in the first experiment showed no sensitivity to color changes at transfer, responding just as rapidly as they did in the last training block, but subjects in the second experiment showed large costs of changing color at transfer, responding 83 ms slower than they did in the last training block. Both of these results are consistent with our hypothesis: Subjects showed no sensitivity to color changes when color was not reported explicitly, and they showed larger costs of changing color when it was reported explicitly.

The experiments

We conducted four experiments to examine the encoding of location information during automatization. Each experiment involved a training period, during which some degree of automaticity was produced (see below), and a transfer period, during which encoding of location during automatization was assessed. The task was the same category search task that we used in previous articles (Boronat & Logan, 1997; Logan & Etherton, 1994; Logan et al., in press), requiring subjects to search through two-word displays for members of a target category (e.g., metals). Targets, nontargets, and distractors appeared in consistent locations throughout training, and their locations were varied at transfer. If subjects encoded location during training, their performance should be disrupted when location changed at transfer.

The four experiments differed in their requirements about reporting the location of the target. Experiment 1 did not required explicit report of location in training or in transfer, Exp. 2 required explicit report of location in both training and transfer, Exp. 3 required explicit report of location in transfer but not in training, and Exp. 4 required explicit report of location in training but not in transfer. Together, the experiments formed a 2 × 2 factorial design, in which report or no report of location was crossed with training and transfer.

Producing and assessing automaticity

Automaticity was produced by training subjects under *consistent mapping* conditions (Shiffrin & Schneider, 1977). Subjects searched for members of a target category, and mapping was consistent in that the target category was the same throughout training and the specific examples presented were the same throughout training. Practice with consistent mapping produces the changes associated with automatization: a reduction in reaction time, a reduction in load effects, and a reduction in dual-task interference (Logan & Etherton, 1994).

Subjects received 16 blocks of training trials, and each example of the target category was presented once per block. This may seem like a small amount of practice for an automaticity experiment, but we have shown repeatedly that extensive training is not necessary to produce the qualitative changes associated with automatization (Boronat & Logan, 1997; Logan, 1988, 1990; Logan & Klapp, 1991). Logan and Etherton (1994) compared large (64-block) and small (16-block) amounts of practice on the same category search task used in the present experiments and found the same qualitative effects at both levels of practice. There was a power-function reduction in reaction time, a reduction in load effects, and a reduction in dual-task interference at both levels of practice. Moreover, the transfer effects (costs from changing word pairing in divided attention and dual-task conditions; lack of cost in focused attention) were the same at the two levels of practice. Because their experiments were so similar to the present ones (also see Boronat & Logan, 1997), we did not test for automatization as rigorously as they did. We defined automatization in terms of a power-function reduction in reaction time. We did not test for a reduction in load effects of dual-task interference with practice.

Experiment 1: No report in training, no report at transfer

In the first experiment, subjects performed the category search task without having to report target location in training or in transfer. The purpose was to see whether location information would be encoded when subjects did not have to report it explicitly. The combined theory predicts more sensitivity to changes in location at transfer when explicit report is required than when it is not required. A strong interpretation predicts no sensitivity to changes in location when explicit report is not required.

Method

Subjects. The subjects were 32 volunteers from an Introductory Psychology course.

Apparatus and stimuli. The stimuli were 64 words used by Logan and Etherton (1994). They were drawn from four categories in the Battig and Montague (1969) norms, with 16 words in each category. The categories were *metals*, *countries*, *vegetables*, and *articles of furniture*. The words are presented in the Appendix. The categories were matched with respect to frequency of mention in the Battig and Montague norms, prototypicality in the Uyeda and Mandler (1980) norms, word frequency in the Kucera and Francis (1967) norms, and word length in letters. Summary statistics for these measures are presented in Table 1. The only significant differences between categories in these measures were in word frequency, where the difference between the highest- and lowest-frequency categories was significant. Word frequency is not an important variable in category verification tasks, at least when the exemplars come from narrowly defined categories, like ours, and are repeated often, as in our experiments (Balota & Chumbley, 1984; Mayall & Humphreys, 1996; Monsell, Doyle, & Haggard, 1989). Moreover, we counterbalanced assignment of categories to experimental conditions, so frequency effects, if there were any, would not contribute to the differences we were interested in.

The words were displayed on Amdek model 722 color monitors driven by IBM PC XT and AT computers. There were four computers, each facing a different wall of a large room, so that several subjects could be tested at the same time without distracting each other.

Two words were displayed on each trial, one above the other. The words were presented in the center of the screen but left-justified. Their initial letters appeared in column 33 of row 12 and row 13 on the standard 80 × 24 IBM text screen. The words were written in lowercase with the first letter capitalized. Viewed at a distance of 60 cm, single words subtended .48° of visual angle in height and minimum of .76° and a maximum of 2.29° in length. The two-word displays subtended 1.14° of visual angle vertically.

Each word pair was preceded by a fixation and warning display. It consisted of two lines of seven dashes centered in the screen. One line of dashes appeared one line above the top word (i.e., row 11, columns 32–38), and one appeared one line below the bottom word (i.e., row 14, columns 32–38). Viewed at a distance of 60 cm, the fixation and warning display subtended 1.62° of visual angle horizontally and 1.72° vertically.

Each trial began with the fixation and warning display exposed for 500 ms. That display was extinguished and immediately replaced by a word pair, which was exposed for 1000 ms. Then the screen went blank for 2000 ms until the next trial began. Subjects responded by pressing the "z" and "/" keys on the bottom row of the standard QWERTY keyboard.

Procedure. The experiment was organized in blocks of 32 trials, in which the 64 words were paired and each pair was presented once. Subjects were tested in Logan and Etherton's (1994) consistent-pairing condition: The words were paired randomly at the beginning of the experiment and the pairing remained the same throughout training and transfer, although the order in which the pairs were presented was randomized each block. A different random pairing was constructed for each subject.

There were two basic trial types – target present and target absent – and 16 of each type were presented in each block. On *target present* trials, one word was selected from the target category and one word was selected from one of two distractor categories. On *target absent* trials, one word was selected from a fourth, nontarget category and the other was selected from one of two distractor categories. Each of the four categories was used equally

Table 1 Means and standard deviations (*in brackets*) of measures of word frequency, frequency of mention, prototypicality, and word length for the 16 words of each category

Measure	Metals	Countries	Vegetables	Furniture
Word frequency[a]	18.9 (15.2)	51.4 (60.9)	8.8 (11.7)	47.8 (64.5)
Frequency of mention[b]	160 (110)	145 (99)	161 (91)	153 (144)
Prototypicality[c]	2.28 (.97)	2.27 (.36)	2.52 (.53)	2.43 (.83)
Word length	5.81 (1.80)	6.56 (1.55)	6.63 (1.93)	5.63 (1.89)

[a] From Kucera and Francis (1967); [b] from Battig and Montague (1969); [c] from Uyeda and Mandler (1980)

often as targets, nontargets, and each of the two distractor categories. The categories were assigned to these roles with a balanced Latin square.

Targets appeared equally often in the top and bottom positions in the display, as did nontargets and members of each of the two distractor categories. However, specific words were presented consistently in one position or the other. For example, if "Canada" was on top and "Steel" was on the bottom in the first block, they remained in those positions throughout training. After training, there was one transfer block of 32 trials in which the locations of targets and distractors were reversed, as were the locations of nontargets and distractors.

Subjects were given written instructions that described the task, told them the name of their target category, and told them which keys to press to indicate target presence and absence. Half of the subjects indicated target presence with their right hands and target absence with their left hands, and half did the opposite. Subjects were told to rest their index fingers lightly on the keys throughout the experiment. Subjects were not told about the number or the nature of the nontarget and distractor categories.

After subjects read the instructions, the experimenter summarized them and answered questions. Then the experiment began. Subjects were allowed brief rests every 128 trials (4 blocks). The last rest was just before the transfer trials.

Results

Training

The mean reaction times for target-present the target-absent responses and the mean error rates in the 16 training blocks are presented in Fig. 1. Reaction time decreased and accuracy increased with practice. The speed-up in reaction time was negatively accelerated, with the largest gains in the early trials, which is characteristic of the power-function speed up that is the hallmark of automatization (Logan, 1992; Newell & Rosenbloom, 1981). Power functions were fitted to the reaction time data. The lines in Fig. 1 represent the fitted functions; the points represent the observed data. Measures of goodness of fit and the parameters of fitted functions are presented in Table 2. Overall, the fits were good.

Reaction times for target-present responses were faster than reaction times for target-absent responses, reflecting the usual tendency for "yes" responses to be faster than "no" responses and possibly reflecting self-terminating search: Subjects could respond "yes" after finding the target, which could involve inspecting only one word; "no" responses required inspecting both words.

Reaction times and accuracy data were subjected to 2 (target present vs. absent) × 16 (practice block) ANOVAs, using $p < .05$ as the significance level. The ANOVA on reaction times found significant main effects of target presence, $F(1, 31) = 25.54$, $MSE = 6910.89$, and practice block, $F(15, 465) = 31.58$, $MSE = 4611.58$, and a significant interaction between target presence and practice, $F(15, 465) = 2.49$, $MSE = 1349.15$.

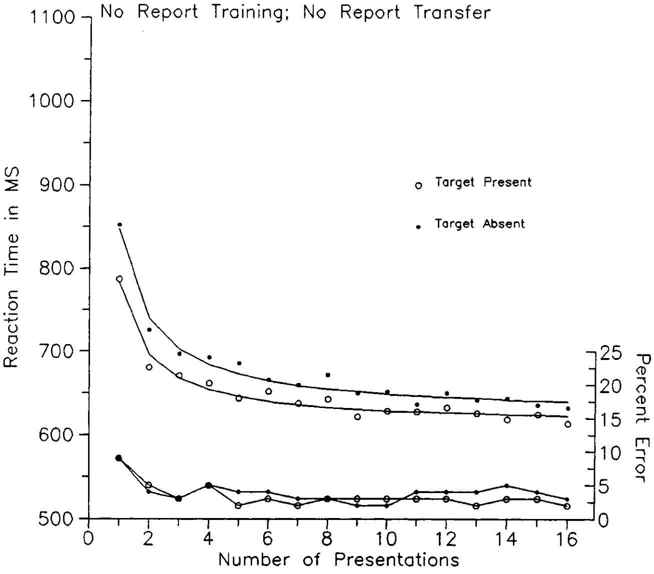

Fig. 1 Mean reaction times (*top two lines*, *left-hand Y-axis*) and error rates (*bottom two lines*, *right-hand Y-axis*) for target-present (*open circles*) and target-absent (*filled circles*) responses from the training phase of Exp. 1 as a function of number of presentations. (For the reaction times, *the lines* represent the best-fitting power function, and *the circles* represent the observed data)

Table 2 Power function fits to mean reaction times from Exps. 1–4. r^2 = squared correlation between observed and predicted values; *rmsd* = root mean squared deviation between observed and predicted values in ms; *a*, *b*, and *c* are parameters of the power function RT = $a + bN^c$, where RT = reaction time and N = the number of practice trials

Experiment	r^2	*rmsd*	*a*	*b*	*c*
1. Present	.969	7.09	614	169	1.040
1. Absent	.977	7.92	624	223	.945
2. Present	.962	8.55	671	196	.731
2. Absent	.985	8.59	624	303	.917
3. Present	.955	7.44	638	148	.980
3. Absent	.993	4.56	609	249	.660
4. Present	.964	8.59	633	215	.590
4. Absent	.977	10.38	575	300	.786

The only significant effect in the ANOVA on the accuracy scores (percentage of correct responses) was the main effect of practice block, $F(15, 465) = 7.00$, $MSE = 21.89$. The main effect of target presence and the interaction between target presence and practice was not significant, both Fs < 1.0.

Transfer

Mean reaction times and percent correct scores for the last block of training and the transfer block for target-present and target-absent responses are presented in Table 3. Mean reaction time slowed by 24 ms and accuracy dropped by 3.5%, averaged over target-present and target-absent responses. These data suggest that information about the location of targets, nontargets, and distractors was encoded in the memory trace, and the retrieval task was sensitive to it. However, the

Table 3 Mean reaction times and percentage of correct responses (*in brackets*) for same and different location trials and costs of changing location in Exps. 1–4. Cost = Different – Same

Exp.	Report in		Location				Cost		Target
	Training	Transfer	Same		Different				
1	No	No	614	(98)	634	(92)	20	(-6)	Present
			633	(97)	660	(96)	27	(-1)	Absent
2	Yes	Yes	705	(93)	772	(91)	67	(-2)	Present
			646	(98)	655	(99)	12	(1)	Absent
3	No	Yes	743	(93)	778	(88)	35	(-5)	Present
			670	(99)	684	(99)	14	(0)	Absent
4	Yes	No	602	(90)	627	(95)	25	(5)	Present
			582	(90)	592	(87)	10	(-3)	Absent

transfer cost was relatively small (e.g., compared to the 97-ms cost of changing target pairing after the same amount of practice in Logan & Etherton, 1994; see also Exp. 2).

The mean reaction times and percent correct scores were analyzed in 2 (location same vs. different) × 2 (target present vs. absent) ANOVAs. In the reaction time ANOVA, the main effect of location change was significant, $F(1, 31) = 13.74$, $MSE = 1275.47$, as was the main effect of target presence, $F(1, 31) = 4.87$, $MSE = 3385.29$, but the interaction between location change and target presence was not, $F < 1.0$. There were no significant effects in the accuracy ANOVA.

Discussion

The power-function speed-up suggested that some degree of automatization occurred during training (for converging evidence, see Boronat & Logan, 1997; Logan & Etherton, 1994). The transfer results suggest that target location was encoded to some extent, even when it did not have to be reported explicitly. Changing location at transfer slowed reaction time by 24 ms. This result is inconsistent with the strong interpretation of the combined theory, which predicts no encoding of location information when explicit report is not required.

Experiment 2: Report in training, report at transfer

In the second experiment, subjects were required to report target location explicitly in both training and transfer. According to our combined theory of attention and automaticity, subjects should be sensitive to changes in location at transfer when explicit report is required. Moreover, their sensitivity to changes in location should be greater in Exp. 2, where explicit report is required, than in Exp. 1, where explicit report was not required.

Subjects in Exp. 2 saw the same two-word displays as subjects in Exp. 1 and searched them for members of the same target categories. If there was no target in the display, they pressed one key to indicate target absence, just like subjects in Exp. 1. However, if there was a target in the display, they pressed one of two keys to indicate its location – one if the target appeared in the top position and another if it appeared in the bottom position.

Method

Subjects. The subjects were 32 volunteers from an Introductory Psychology course. None had served in the previous experiment.

Apparatus and stimuli. The apparatus and stimuli were the same as those used in Exp. 1. The only difference was in the keys subjects pressed to register their responses. We used the “z”, “x”, period, and “/” keys.

Procedure. The procedure was the same as in Exp.1, except that subjects were required to report the location of the target if it appeared in the display. Half of the subjects pressed “x” for a target in the top position, “z” for a target in the bottom position, and “/” if there was no target in the display. The other half pressed the period key for a target in the top position, “/” for a target in the bottom position, and “z” if there was no target in the display. Targets, nontargets, and distractors appeared in the same positions consistently throughout training and reversed positions at transfer.

Results

Training

The mean reaction times for target-present and target-absent responses and the mean error rates in the 16 training blocks are presented in Fig. 2. Reaction time decreased and accuracy increased with practice. Power functions were fitted to the reaction time data. The lines in Fig. 2 represent the fitted functions; the points represent the observed data. Measures of goodness of fit and the parameters of fitted functions are presented in Table 2. Again, the fits were good.

Reaction times for target-present responses were faster than reaction times for target-absent responses only for the first two blocks. After that, they were slower, reflecting the extra processing involved in discriminating and reporting the position of the target.

Reaction times and accuracy data were subjected to 2 (target present vs. absent) × 16 (practice block)

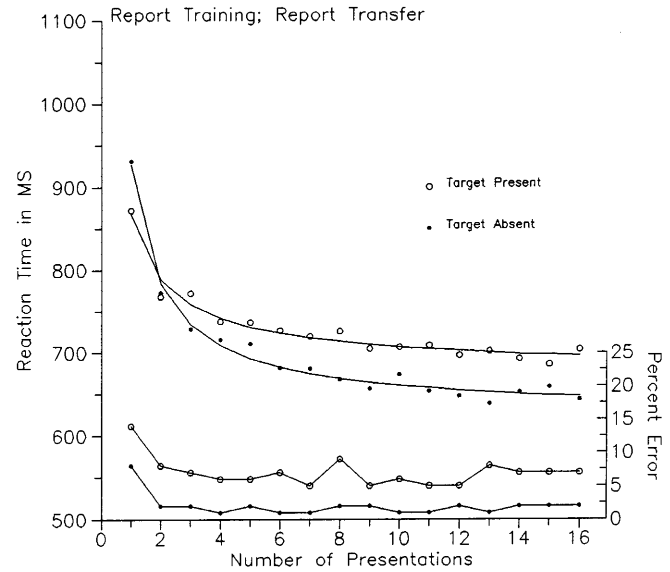

Fig. 2 Mean reaction times (*top two lines*, *left-hand Y-axis*) and error rates (*bottom two lines*, *right-hand Y-axis*) for target-present (*open circles*) and target-absent (*filled circles*) responses from the training phase of Exp. 2 as a function of number of presentations. (For the reaction times, *the lines* represent the best-fitting power function, and *the circles* represent the observed data)

ANOVAs. The ANOVA on reaction times found significant main effects of target presence, $F(1, 31) = 23.50$, $MSE = 1251.00$, and practice block, $F(15, 465) = 66.03$, $MSE = 3334.08$, and a significant interaction between target presence and practice, $F(15, 465) = 10.24$, $MSE = 1418.59$. The ANOVA on the accuracy scores produced significant main effects of target presence, $F(1, 31) = 21.72$, $MSE = 290.09$, and practice block, $F(15, 465) = 8.23$, $MSE = 26.80$. The interaction between target presence and practice was not significant, $F(15, 465) = 1.02$, $MSE = 22.93$.

Transfer

The mean reaction times and accuracy data from the last training block and the transfer block are presented in Table 3. Subjects reported location on target-present trials in training and in transfer, and the change in location at transfer produced a substantial cost in reaction time on target-present trials. By contrast, the cost for similar changes in the locations of nontargets and distractors on target-absent trials was negligible. The target-present data suggest that information about target location was encoded in the memory trace. The target-absent data suggest either that the locations of nontargets and distractors were not encoded, or that the retrieval task, which did not require report of location, was not sensitive to that aspect of the memory trace, or both.

The mean reaction times and percent correct scores were analyzed in 2 (location same vs. different) × 2 (target present vs. absent) ANOVAs. In the reaction time ANOVA, the main effect of location change was significant, $F(1, 31) = 15.33$, $MSE = 2917.77$, as was the main effect of target presence, $F(1, 31) = 68.50$, $MSE = 2917.77$, and the interaction between location change and target presence, $F(1, 31) = 12.42$, $MSE = 1680.91$. In the accuracy ANOVA, the only significant effect was target presence, $F(1, 31) = 37.50$, $MSE = 37.63$.

Discussion

Reaction times decreased as a power function of the number of practice trials during training, which suggests that some degree of automatization was obtained (see also Logan & Etherton, 1994). There was a large cost of changing target location at transfer, which suggests again that location was encoded during training. The cost of changing location was much stronger in this experiment than in Exp. 1 (67 vs. 20 ms on target-present trials), suggesting that the requirement to report target location explicitly during training resulted in a stronger encoding of location information, which is consistent with the predictions of our combined theory of attention and automaticity. The contrast between Exps. 1 and 2 was replicated conceptually within Exp. 2 itself: Transfer costs were significantly higher for targets, whose locations were reported explicitly, than for nontargets, whose locations were not reported explicitly (67 vs. 12 ms, respectively).

Experiment 3: No report in training, report in transfer

There are three possible interpretations for the costs of changing location in Exp. 2. The requirement to report location explicitly could have caused location to be encoded during training, as we predicted. Alternatively, the requirement to report location explicitly could make the retrieval process more sensitive to whatever location information resided in the memory trace. The third possibility is that the requirement to report location explicitly affected both encoding and retrieval. The remaining experiments were designed to distinguish between these alternatives. In Exp. 3, subjects were trained under standard category search instructions (i.e., no report of target location required) and transferred to conditions that required explicit target location report. If the increased transfer costs of explicit target location report in Exp. 2 were due only to retrieval, then the transfer costs in Exp. 3 should be the same magnitude as those in Exp. 2. However, if the increased costs in Exp. 2 were due to encoding as well as retrieval, then the transfer costs in Exp. 3 should be smaller than those in Exp. 2, though perhaps larger than those in Exp.1.

Method

Subjects. The subjects were 32 volunteers from an Introductory Psychology course. None had served in the previous experiments.

Apparatus and stimuli. The apparatus and stimuli were the same as those used in Exps. 1 and 2. The only difference was in the keys that subjects pressed to register their responses. They used the "z" and "/" keys in training and the "z", "x", period, and "/" keys at transfer.

Procedure. The training procedure was the same as in Exp.1, in that subjects did not report the position of the target, and the transfer procedure was the same as in Exp. 2, in that subjects reported the position of the target on target-present trials. Unlike the preceding experiments, the transfer block involved 64 trials, half with target, nontarget, and distractor words in the same position they appeared in during training, and half with words in the opposite position. The cost of changing position was assessed by comparing these two trial types. It was not reasonable to compare the last training block with the transfer block, as we did in the previous experiments, because the response requirements changed (i.e., from reporting position to not reporting position). Response requirements had strong effects on reaction times, and we did not want to confound them with the effects of changing position.

In training, half of the subjects pressed "z" if there was a target in the display and "/" if there was no target in the display. The other half pressed the "/" key if there was a target and "z" if there was no target. In transfer, subjects who had pressed "z" for targets and "/" for nontargets now pressed "x" for targets in the top position, "z" for targets in the bottom position, and "/" for all nontargets. Subjects who had pressed "/" for targets and "z" for nontargets now pressed the period key for targets in the top position, "/" for targets in the bottom position, and "z" for all nontargets.

Results

Training

The mean reaction times for target-present and target-absent responses and the mean error rates in the 16 training blocks are presented in Fig. 3. Reaction time decreased as a power function of practice, and accuracy increased with practice. Power functions were fitted to the reaction time data (the lines in Fig. 3 represent the fitted functions; the points represent the observed data). Measures of goodness of fit and the parameters of fitted functions are presented in Table 2. Once again, the fits were good.

Reaction times for target-present responses were faster than reaction times for target-absent responses, reflecting the usual tendency for "yes" responses to be faster than "no" responses and, possibly, self-terminating search. The difference diminished with practice, suggesting that subjects may have responded to the whole display for both response types (Logan & Etherton, 1994).

Reaction times and accuracy data were subjected to 2 (target present vs. absent) × 16 (practice block) ANOVAs. The reaction time ANOVA found significant main effects of target presence, $F(1, 31) = 16.48$, $MSE = 6937.74$, and practice block, $F(15, 465) = 40.50$, $MSE = 3276.74$, and a significant interaction between target presence and practice, $F(15, 465) = 5.48$, $MSE = 1393.15$.

The ANOVA on the accuracy scores revealed a significant main effect of target presence, $F(1, 31) = 6.17$, $MSE = 198.64$, a significant main effect of practice block, $F(15, 465) = 8.06$, $MSE = 48.06$, and a significant interaction between them, $F(15, 465) = 5.48$, $MSE = 24.03$.

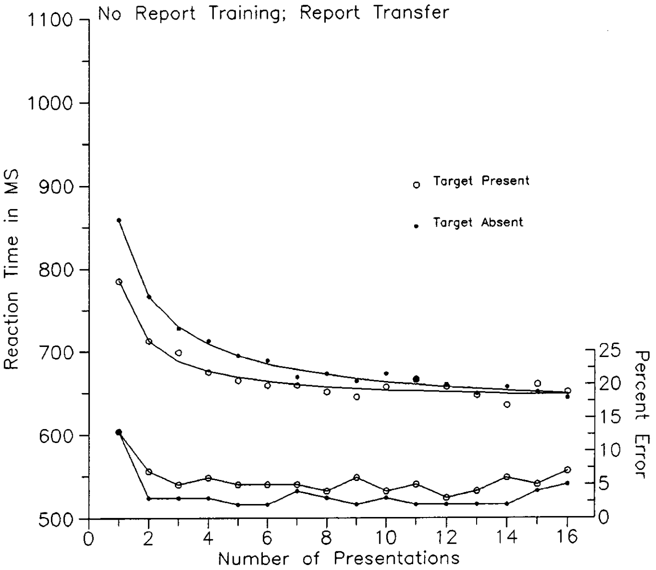

Fig. 3 Mean reaction times (*top two lines*, *left-hand Y-axis*) and error rates (*bottom two lines*, *right-hand Y-axis*) for target-present (*open circles*) and target-absent (*filled circles*) responses from the training phase of Exp. 3 as a function of number of presentations. (For the reaction times, *the lines* represent the best-fitting power function, and *the circles* represent the observed data)

Transfer

The mean reaction times and accuracy data from the last training block and the transfer block are presented in Table 3. Subjects did not report target location during training, but they did report it in transfer. There was a moderate cost of changing location on target-present trials and a smaller cost of changing it on target-absent trials. These data suggest that the training task, which did not require target location report, did not lead subjects to encode location very often. Cost for changing target location was larger than the one observed with the same training task in Exp. 1 but smaller than the one observed with the same transfer task in Exp. 2. These differences must be due to a lower likelihood of encoding location in tasks that do not require it to be reported explicitly.

The main effect of location change was significant, $F(1, 31) = 9.82$, $MSE = 2041.58$, as was the main effect of target presence, $F(1, 31) = 45.57$, $MSE = 4899.39$. The interaction between target presence and location change approached significance, $F(1, 31) = 3.27$, $p < .09$, $MSE = 1071.45$, albeit from afar. In the accuracy ANOVA, the main effect of target presence was significant, $F(1, 31) = 47.48$, $MSE = 45.01$, as was the main effect of location change, $F(1, 31) = 15.64$, $MSE =$

14.61, and the interaction between target presence and location change, $F(1, 31) = 14.03$, $MSE = 15.91$.

Discussion

Reaction times decreased as a power function of practice trials in training, suggesting that some degree of automatization obtained (see also Logan & Etherton, 1994). Changing location at transfer also produced significant costs, suggesting that location information had been encoded during training. The cost of changing target location in this experiment (35 ms) was greater than the one observed in Exp. 1 (20 ms), which required no report of target location throughout training and transfer, but smaller than the one observed in Exp. 2 (67 ms), which required explicit report of target location in training and in transfer.

These results support two conclusions about encoding and retrieval: First, the standard category search procedure used in training in Exps. 1 and 3 led subjects to encode relative location more often than the transfer results of Exp. 1 suggested. The transfer costs in Exp.1 were small partly because the retrieval task at transfer was not very sensitive to relative location information in the memory trace. Second, the results of Exp. 3 suggest that explicit report of target location affects both encoding and retrieval. If it affected only retrieval, the transfer costs in Exp. 3 should have been just as large as the transfer costs in Exp. 2, but they were smaller. Thus, the larger transfer costs in Exp. 2 must have reflected a stronger tendency to encode relative location information during training as well as a greater sensitivity to relative location information at transfer.

Experiment 4: Report in training, no report in transfer

The fourth experiment required subjects to report target location explicitly in training but not in transfer. It was intended to provide converging evidence that the requirement to report target location explicitly affected both encoding and retrieval. If explicit report of target location affected only encoding, then the costs of changing location at transfer should be just as strong in Exp. 4 as they were in Exp. 2. If explicit report of target location affected encoding as well as retrieval, then transfer costs should be smaller in Exp. 4 than in Exp. 2, although they may be larger than the transfer costs in Exp. 1.

A second purpose was to assess the sensitivity of the standard category search procedure to relative location information in the memory trace. The requirement to report target location explicitly during training should guarantee the encoding of relative location information. If standard category search, viewed as a retrieval task, is sensitive to this information, the cost of changing location at transfer should be greater than the costs observed in Exp. 1, where location information was less likely to be encoded relatively.

Method

Subjects. The subjects were 32 volunteers from an Introductory Psychology course. None had served in the previous experiments.

Apparatus and stimuli. The apparatus and stimuli were the same as those used in Exps. 1 and 2. The only difference was in the keys subjects pressed to register their responses. They used the "z", "x", period, and "/" keys in training and the "z" and "/" keys at transfer.

Procedure. The training procedure was the same as in Exp. 2, in that subjects reported the position of the target on target-present trials, and the transfer procedure was the same as in Exp. 1, in that subjects did not report target position. The transfer block involved 64 trials, like Exp. 3, half with target, nontarget, and distractor words in the same position they appeared in during training, and half with words in the opposite position. The cost of changing position was assessed by comparing these two trail types.

In training, half of the subjects pressed "x" for a target in the top position, "z" for a target in the bottom position, and "/" if there was no target in the display. The other half pressed the period key for a target in the top position, "/" for a target in the bottom position, and "z" if there was no target in the display. In transfer, subjects who had pressed "x" or "z" for targets and "/" for nontargets now pressed "x" for all targets and "/" for all nontargets. Subjects who had pressed the period key and "/" for targets and "z" for nontargets now pressed "/" for all targets and "z" for all nontargets.

Results

Training

The mean reaction times for target-present and target-absent responses and the mean error rates in the 16 training blocks are presented in Fig. 4. Reaction time decreased and accuracy increased with practice. Power functions were fitted to the reaction time data. The lines in Fig. 4 represent the fitted functions; the points represent the observed data. Measures of goodness of fit and the parameters of fitted functions are presented in Table 2. The fits were good.

Reaction times for target-present responses were slower than reaction times for target-absent responses except for the first block, reflecting the extra processing involved in discriminating and reporting the position of the target.

Reaction times and accuracy data were subjected to 2 (target present vs. absent) × 16 (practice block) ANOVAs. The ANOVA on reaction times found significant main effects of target presence, $F(1, 31) = 46.87$, $MSE = 15525.20$, and practice block, $F(15, 465) = 76.40$, $MSE = 2883.93$, and a significant interaction between target presence and practice, $F(15, 465) = 8.60$, $MSE = 1119.56$.

The ANOVA on the accuracy scores produced significant main effects of target presence, $F(1, 31) = 35.65$, $MSE = 205.36$, and practice block, $F(15, 465) = 15.79$, $MSE = 25.02$. The interaction between target presence and practice was not significant, $F < 1.0$.

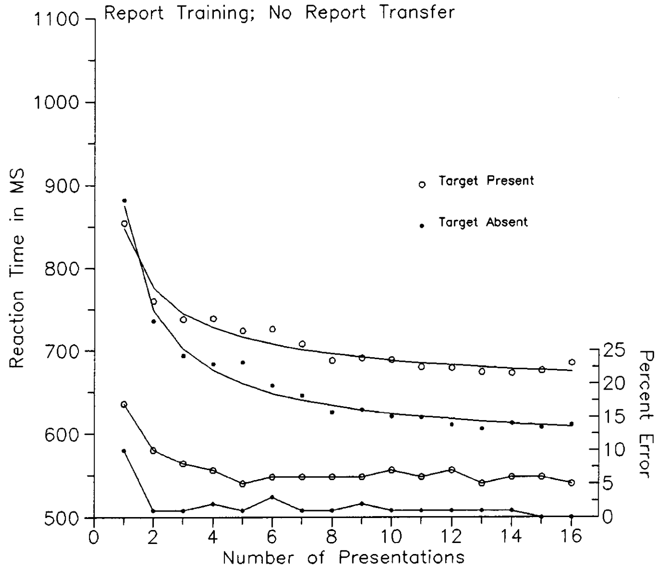

Fig. 4 Mean reaction times (*top two lines, left-hand Y-axis*) and error rates (*bottom two lines, right-hand Y-axis*) for target-present (*open circles*) and target-absent (*filled circles*) responses from the training phase of Exp. 4 as a function of number of presentations. (For the reaction times, *the lines* represent the best-fitting power function, and *the circles* represent the observed data)

Transfer

The mean reaction times and accuracy data from the transfer block are presented in Table 3. Subjects reported target location during training but not during transfer. Changing target location at transfer had a small cost that was larger than the cost associated with changing nontarget and distractor locations. However, the cost in reaction time was offset by a gain in accuracy, so it may reflect a speed-accuracy tradeoff rather than a real sensitivity to the changed location. These data suggest that the retrieval task at transfer, which did not require report of target location, was not very sensitive to relative location information in the memory trace. The data from Exp. 2 suggest that relative target location was probably stored in the memory traces acquired during training, because changing location produced substantial cost when location had to be reported. The cost associated with changing location was much smaller in this experiment, which did not require target location report, and it was compromised by a speed-accuracy tradeoff.

The mean reaction times and percent correct scores were analyzed in 2 (location same vs. different) × 2 (target present vs. absent) ANOVAs. In the reaction time ANOVA, the main effect of location change was significant, $F(1, 31) = 18.55$, $MSE = 507.73$, as was the main effect of target presence, $F(1, 31) = 11.69$, $MSE = 2089.71$. The interaction between target presence and location change approached significance, $F(1, 31) = 2.88$, $p < .10$, $MSE = 671.81$. In the accuracy ANOVA, only the main effect of target presence was significant, $F(1, 31) = 8.80$, $MSE = 26.27$.

Discussion

The training results suggested that automatization occurred, in that reaction time decreased as a power function of practice. The transfer results suggested that location information had been encoded during automatization, in that there was a significant cost of changing location at transfer. The cost of changing target location (25 ms) was slightly larger than the one observed after similar retrieval conditions in Exp. 1 (20 ms) but much smaller than the one observed after similar encoding conditions in Exp. 2 (67 ms). These results support two conclusions. First, they suggest that the standard category search procedure is sensitive to the presence of location information in the memory trace, but less sensitive than a retrieval task that requires explicit report of target location. Second, the results converge on the evidence from Exp. 3 that suggests that the requirement to report target location explicitly affects both encoding and retrieval. If it affected only encoding, then the transfer costs should have been just as large as the ones in Exp. 2.

Experiments 1–4 compared

The logic of Exps. 1–4 rests on comparisons of transfer costs between experiments. We concluded that the costs in Exp. 2 were larger than the costs in Exps. 1, 3, and 4, and that the costs in Exps. 3 and 4 were intermediate between the small costs in Exp. 1 and the large costs in Exp. 2. In order to provide statistical support for these conclusions, we compared the transfer costs in Exps. 1–4 in a single 2 (report vs. no report of location in training) × 2 (report vs. no report of location at transfer) × 2 (target present vs. absent) ANOVA on differences scores calculated by subtracting same-location reaction times from different-location reaction times. This ANOVA compared data from subjects tested at different times by different experimenters, and it compared difference scores computed between blocks (Exps. 1 and 2) with some computed within blocks (Exps. 3 and 4), so the results were potentially confounded. Nevertheless, the logic of the series of experiments depends on between-experiment comparisons, and we thought it was better to test them statistically even if the ANOVA was not completely appropriate than not to test them at all and rely on qualitative comparisons.

The main purpose of the ANOVA was to compare transfer costs between experiments, and we did so by computing Fisher's least significant difference (LSD) test, using the error from the 3-way interaction (2101.38; $df = 124$). By this criterion, differences larger than 11 ms were significant at $p < .05$, and differences larger than 15 ms were significant at $p < .01$. Those comparisons revealed (a) significant transfer cost for target-present responses in all experiments ($p < .01$), (b) significant transfer costs for target-absent responses in all but Exp. 4 ($p < .05$), (c) significantly larger transfer cost for target-present responses in Exp. 2 than in Exps. 1, 3, and 4 ($p < .01$), and (d) significantly larger transfer cost for target-present responses in Exp. 3 than in Exp. 1 ($p < .01$). These results confirm the conclusions about between-experiment differences that were reached in the separate Discussion sections.

General discussion

The experiments were designed to determine whether location information was encoded during automatization when subjects did and did not have to report location explicitly. Each experiment showed evidence of automatization, in that reaction time decreased as a power function of practice. The power function speed-up by itself is not strong evidence of automatization, but Boronat and Logan (1997) and Logan and Etherton (1994) showed that the same amount of practice on the same task with the same stimuli also produced a reduction in load effects and a reduction in dual-task interference as well as a power-function speed-up in subjects from the same population. Thus, it seems reasonable to interpret the present power-function speed-up as evidence for automatization.

Each experiment showed evidence that location information had been encoded during automatization, in that there were significant costs when target location changed at transfer. The costs in Exp. 1 falsify the strong prediction, drawn from our combined theory, that location information will not be encoded when location is not reported explicitly. The costs in Exp. 1 challenge the general prediction that subjects will not learn about selection attributes (i.e., attributes to which subjects give priority by manipulating the π parameter).

The cost in Exp. 2 confirms the prediction that location information will be encoded when it must be reported explicitly. Moreover, the cost in Exp. 2 was significantly larger than the cost in Exp. 1, which confirms the prediction that location information is more likely to be encoded when it must be reported explicitly.

Experiments 3 and 4 converge on the conclusions drawn from Exps. 1 and 2. Experiment 3 suggests that the standard category search task used in Exp. 1 may have underestimated the encoding of location information. Subjects in Exp. 3 were not required to report location explicitly during training, but when they were required to do so at transfer, the costs of changing location were significantly larger than the costs observed in Exp. 1. Thus, a retrieval task that does not require explicit report of location may not be very sensitive to the presence of location information in the memory trace.

Experiment 4 provided further evidence for the insensitivity of the standard category search task to the presence of location information in the memory trace. Subjects reported location information explicitly during training, which in theory and in line with the results of Exp. 2 should have caused location to be encoded in the memory trace. However, at transfer, when explicit report was not required, the transfer costs were no larger than those observed in Exp. 1 and significantly smaller than those observed in Exp. 2.

Implications for the combined theory

The results can be interpreted three ways, with respect to the combined theory. First, the theory may be wrong. Location information may be encoded even though it is not reported explicitly. Second, the theory may be incomplete. Some processes outside the theory may be responsible for the costs of changing location when it was not reported explicitly. Third, there may be problems with the experiments that weaken the evidence against the theory. We shall consider each in turn.

The theory may be wrong

Our interpretation of Bundesen's (1990) theory was that explicit representations were only formed for reported attributes (i.e., attributes for which β was set high). Selection attributes (for which π was set high) did not result in explicit representations in short-term memory. Bundesen does not explicitly endorse this interpretation and may prefer an alternative (see, e.g., Logan & Bundesen, 1996). We assumed further that subjects only learned (i.e., encoded into long-term memory) that which was represented explicitly into short-term memory. A valid interpretation of the experiments is that our assumptions are wrong.

However, the assumptions are only partly wrong. The combined theory also predicted that subjects would be more likely to encode things that were reported explicitly than things that were not, and this was confirmed in the contrast between Exps. 1 and 2. This contrast is inconsistent with the idea that all attributes of a stimulus are encoded into short-term memory regardless of whether they are reported explicitly. Thus, the data constrain the various readings of Bundesen's (1990) theory.

The theory may be incomplete

It is possible that the theory is right as far as it goes, but it does not provide a complete description of all the learning that goes on during automatization. That is, subjects may encode into long-term memory only that which is represented explicitly in short-term memory, and subjects may represent explicitly in short-term memory only the reported attributes (for which β is high), as we assumed, but some other processes besides long-term memory contribute to the performance benefits that result from automatization.

One possibility, suggested by many but formalized by Ratcliff and McKoon (1997), is that the perceptual processes that generate the categorizations are modified by experience. This kind of modification may be responsible for the costs of changing location when location was not reported explicitly, while the learning mechanisms in our combined theory were responsible for the costs when location was reported explicitly. This explanation is troublesome in two respects.

First, the associations responsible for the costs of changing location are complex, involving arbitrary conjunctions of three different kinds of attributes: location, word category, and response. The kinds of associations that Ratcliff and McKoon (1997) envisioned were much simpler: associations between shapes and word identities. It is not clear that their theory would account for the complex conjunctive associations underlying the costs of changing locations.

Second, Ratcliff and McKoon's (1997) theory takes one side of a long-standing debate over the interpretation of dissociations between implicit and explicit memory phenomena, the side that assumes separate memory systems. The other side, which assumes that implicit and explicit memory depend on the same, unitary memory system, has considerable support. Humphreys, Bain, and Pike (1989) and Shiffrin and Steyvers (1997) proposed formal models of memory in which implicit and explicit memory tasks address the same memory traces. This debate is not yet over, so it would be imprudent to take one side or the other without further investigation.

We prefer to think that our theory can provide a complete account of automatization and skill learning, including phenomena of explicit and implicit memory. At least, that is the goal toward which we are working. While theories like Ratcliff and McKoon's (1997) can account for interesting dissociation phenomena, they generally do not provide an account of attention that is as powerful as Bundesen's (1990), and so they do not provide an account of the interactions between attention and automaticity during training and transfer. In other words, our theory may be incomplete, but its competitors are incomplete as well. At this early stage of development, it may be better to reserve judgment about the necessity of going outside our theory to account for experimental results.

The experiments may be problematic

Our experiments may not have provided a very stringent test of the hypothesis that there can be no learning without explicit representation in short-term memory. There was nothing in our experiments to prevent subjects from attending to location when explicit report of location was not required, and it is possible that they attended to it occasionally, forming explicit representations in short-term memory when they did so. These explicit representations could underlie the transfer costs we observed in Exps. 1 and 3, after training without explicit location report.

This problem with the experiments is an example of a general problem in selective attention experiments: It is exceedingly difficult to be sure that subjects do not attend to things they are not instructed to attend to (see, e.g., Hollender, 1986). In past research investigating the role of attention in automatization, we have distinguished between strong and weak versions of the hypothesis that subjects will not learn what they do not attend to. The strong version says that subjects will learn nothing about what they do not attend to; the weak version says the will learn more about what they do attend to than what they do not attend to (see Boronat & Logan, 1997; Logan & Etherton, 1994; Logan et al., 1986). In the past, we have preferred the weak version of the hypothesis because it can be tested readily and because the strong version is exceedingly difficult to test. Perhaps that preference is also appropriate here. The experiments demonstrate clearly that subjects learn more about location when they report it explicitly than when they do not, and perhaps we should weigh that prediction more heavily in evaluating the empirical success of our theory.

Future work on the combined theory

We interpret the present results as providing at least partial support for the combined theory, and this encourages us to develop it further. The next step is a formal unification, bringing together the mathematical representations of the two theories in a common format. This will involve changing some of the assumptions of each of the theories. For example, the instance theory assumes that the finishing times for the runners in the race follow a Weibull distribution, whereas Bundesen's (1990) theory assumes they follow an exponential distribution. The implications of changing these assumptions must be investigated mathematically and empirically.

Moreover, bringing the theories together will involve increasing the specificity of some of the assumptions, such as Bundesen's (1990) assumptions about what gets represented explicitly in short-term memory, and empirical work will have to evaluate the feasibility of the more specific assumptions. Bringing the theories together will also involve making new assumptions, such as our current assumption that explicit representation in short-term memory is a necessary step in forming long-term memory representations. Empirical work will have to evaluate the feasibility of these assumptions as well.

Finally, the theory will have to be contrasted with its competitors formally and empirically, and critical tests of the theories will have to be conducted. At this early stage in the process of theory development, it is hard to anticipate the eventual success of our theory. Given the past success of the instance theory on the one hand and Bundesen's (1990) theory on the other, we are encouraged to forge ahead. Even if the combined theory proves intractible or wrong, we will have learned some important lessons along the way.

Uniqueness of the combined-theory account

A skeptical reader may note that other theories of attention and other theories of automaticity may account for the results of our experiments. This is certainly true. Our account may be unique only in being perhaps the second attempt to explain both attention and automaticity, Schneider's (1985; Schneider & Detweiler, 1987) being the first. At this stage in the development of the theory, we are more interested in testing the assumptions we need to make to combine the instance theory with Bundesen's (1990). There is no point in pitting the combined theory against its competitors if its assumptions are not valid.

In combining the theories, we are faced with choices about the assumptions within each theory and in the interface between them. We need to investigate the alternatives before choosing among them. It seems prudent to explore the theory's potential before casting it in stone and pitting it against its competitors.

The theory promises a unique account in the future. The combined theory will attempt to explain attention and automaticity simultaneously, using a single set of assumptions and a single set of parameters. At present, no theory besides Schneider's (1985) accounts for attention and automaticity simultaneously (and Schneider's account of attention is limited, relative to Bundesen's). One can imagine combining a given theory of attention with a given theory of automaticity and producing an account of the results. The theory of attention could say which object was selected, and the theory of automaticity could say how a response to that object was generated. However, the attentional account need not be constrained by the automaticity account and vice versa. The predictions about the nature and the magnitude of the attentional phenomena could be independent of the predictions about the nature and the magnitude of the automaticity effects. By contrast, in our combined theory, the predictions about attention determine the nature and the magnitude of the predictions about automaticity, and vice versa. For example, the effect of adding another decision to the task (e.g., the explicit location report conditions of Exps. 2–4) should determine changes in the learning curves. Failure to find the predicted constraint would falisify the theory.

At present, we are only at the beginning of the long process involved in combining the theories. We hope that the skeptical reader will reserve judgment about our ability to provide a unique account and consider instead what may be learned from the assumption testing we do along the way. From that perspective, the present experiments document interesting interactions between what must be reported and what is learned that stand on their own as a new contribution.

Conclusions

Are attention and automaticity dependent or independent? The data suggest there are strong dependencies. What is learned during automatization depends on what is attended to and on how attention is deployed (also see Bornat & Logan, 1997; Lassaline & Logan, 1993; Logan 1990; Logan & Etherton, 1994). Subjects learn more about attributes they report explicitly (i.e., reported attributes) than about attributes that guide their attention (i.e., selection attributes; also see Logan et al., 1996).

The theory developed in this article also suggests strong interactions. Attention and automaticity are different sides of the same coin. The theory of attention cannot work without the representational assumptions of the theory of automaticity, and the theory of automaticity cannot work without the processing assumptions of the theory of attention. The formal structure of the theory should allow us to make quantitative predictions about the nature and magnitude of the interactions between attention and automaticity.

Have we settled the issue of the relation between attention and automaticity? It seems unlikely. Researchers who assume independence can marshall data in support of their claims and they can point to theoretical propositions that make their claims seem reasonable. At the very least, we have raised the stakes in the debate by presenting data contrary to independence and proposing a formal theory that explains the dependence.

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Appendix

Words used in the experiments

Metals	Countries	Vegetables	Furniture
Iron	France	Carrot	Chair
Copper	America	Peas	Table
Steel	Russia	Corn	Bed
Gold	England	Bean	Sofa
Aluminum	Germany	Lettuce	Desk
Silver	Canada	Spinach	Lamp
Tin	Italy	Asparagus	Couch
Zinc	Spain	Broccoli	Dresser
Brass	Mexico	Celery	Bureau
Lead	Ireland	Cabbage	Chest
Bronze	Japan	Cauliflower	Bookcase
Platinum	Sweden	Radishes	Cabinet
Nickel	Brazil	Potato	Davenport
Magnesium	Switzerland	Tomato	Footstool
Uranium	Norway	Cucumber	Buffet
Tungsten	Australia	Beets	Bench

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