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What Is Learned During Automatization? II. Obligatory Encoding of Spatial Location

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Six experiments addressed the encoding of location information during automatization, to test a critical prediction of the instance theory of automaticity (G. D. Logan, 1988). Subjects searched 1- or 2-word displays for members of a target category. Specific targets appeared in the same locations consistently throughout training, and then location changed at transfer. Sensitivity to changes in location were assessed with implicit and explicit memory tests. In both tests, sensitivity depended on the number of locations the words could occupy (2 vs. 16). Sensitivity varied with the number of words presented (1 vs. 2) in the implicit test, but not in the explicit test. The results suggest that subjects encoded the locations of the words during automatization, which confirms the predictions of the instance theory.

This article is concerned with what is learned during the acquisition of automaticity and how that learning is expressed during skilled performance. These issues are important practically and theoretically. From a practical perspective, they bear on the transfer of skills following training, suggesting ways to engineer a training program to maximize transfer when the trainees enter the workforce. From a theoretical perspective, they bear on theories of automatization and skill acquisition, especially memory-based theories, which assume that automatic performance depends on retrieval of past solutions from memory. What is learned during automatization and expressed during automatic performance is especially important from the perspective of the instance theory of automaticity (Logan, 1988), which predicts that subjects learn what they attend to during training and express things associated with what they attend to at transfer. The present article tests these predictions, extending them to the encoding of location information.

Obligatory Encoding and the Attention Hypothesis

The instance theory of automaticity rests on three main assumptions: obligatory encoding, which says that attention to an object or event is sufficient to cause it to be stored in memory; obligatory retrieval, which says that attention to an object or event is sufficient to cause things associated with it to be retrieved from memory; and instance representation, which says that each object or event is encoded, stored, and retrieved separately, even if it is an exact repetition of a previous event (Logan, 1988; Logan & Etherton, 1994; Logan, Taylor, & Etherton, 1996). The obligatory encoding and obligatory retrieval assumptions place a heavy explanatory burden on attention. Whether attention can bear that burden is an empirical question that speaks to the core of the instance theory. The theory stands or falls on the answer. My colleagues and I have been trying to answer this question for several years.

The obligatory encoding and obligatory retrieval assumptions lead to a set of predictions we call the attention hypothesis: Subjects should encode the things they attend to but not the things they do not attend to; subjects should retrieve things associated with the things they attend to but not things associated with things they do not attend to.[1] We have tested these predictions and confirmed them several times: Logan and Etherton (1994) showed that subjects encoded relations between words if they attended to both of them but not if they attended to one and ignored the other. Boronat and Logan (1997) showed that focusing attention on one of two words at transfer blocked retrieval of relations between the words that were acquired during training. Logan (1990) showed that transfer depended on the way subjects attended to a stimulus. There was good transfer if subjects interpreted the stimulus in the same way they interpreted it during training but poor transfer if they interpreted it differently. Logan et al. (1996) showed that

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[1]We could not distinguish between a strong version of the attention hypothesis, which says that attention is *necessary* for encoding and retrieval, and a weak version, which says that attention is *sufficient* but not necessary, because of the difficulty of controlling what subjects do with unattended material (see also Boronat & Logan, 1997; Logan & Etherton, 1994). If we found evidence of encoding and retrieval outside the required focus of attention, advocates of the weak view would interpret it as evidence that attention was not necessary, but advocates of the strong view would argue that subjects occasionally paid attention to things they were not required to. The issue is controversial and very difficult, if not impossible, to resolve (see, e.g., Hollender, 1986; Kahneman & Treisman, 1984). Consequently, we focused our analyses primarily on the weak version, demonstrating that attention is an important factor in encoding and retrieval, if not the only one.

subjects encoded the attribute (color) they used to select a target in a two-word display. Lassaline and Logan (1993) showed that subjects did not encode attributes (including color) that were irrelevant to their task set.

The present experiments extend the attention hypothesis to the obligatory encoding and retrieval of location information. This is an important extension, because there are strong reasons to believe that subjects must attend to location in order to select a visual object (reviewed later), and those reasons force the instance theory to predict that location should be encoded during automatization. Failure to confirm this prediction would falsify the instance theory.

The instance theory places a heavy explanatory burden on memory as well as attention. The instance theory regards automaticity as a memory phenomenon, governed by the theoretical and empirical principles that govern memory. We have examined principles of memory in automatization in past research (Logan, 1988, Experiment 5; Logan & Klapp, 1991; also see Zbrodoff, 1995). In this article, memory principles guide the set of hypotheses we explore in searching for alternative interpretations. To foreshadow the results, the first experiment showed no evidence that location was encoded in the task we used in previous investigations of the attention hypothesis, which was bad news for the instance theory. Principles from the memory literature suggested that location may have been encoded but not retrieved due to constraints on the retrieval process. The remaining experiments examined three versions of this retrieval-failure hypothesis to try to save the instance theory.

Obligatory Attention to Location

For the last 15 years, visual spatial attention has been a dominant paradigm in the attention literature, integrating experimental psychology and neuroscience. Important phenomena were discovered and explored. New theories were developed, specific to visual attention, that were more detailed and more sharply focused than the general theories of the 1970s (e.g., Bundesen, 1990; Duncan & Humphreys, 1989; Grossberg, Mingolla, & Ross, 1994; Humphreys & Müller, 1993; LaBerge & Brown, 1989; Logan, 1996; Mozer, 1991; Phaf, van der Heijden, & Hudson, 1990; Sperling & Weichselgartner, 1995; Treisman & Gelade, 1980; Treisman & Gormican, 1988; van der Heijden, 1992; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). All of these theories, except Bundesen's (1990), argue that visual selection is mediated by location (but see extensions of Bundesen's theory by Logan, 1996, and Logan & Bundesen, 1996): In order to select a visual object, one must necessarily attend to its location.

The argument that visual selection is mediated by location is supported by a great deal of evidence: Location is a powerful selection cue (von Wright, 1968, 1970). Cuing the location of a target facilitates its detection when the cue is valid and inhibits it when the cue is invalid (Bashinski & Bacharach, 1980; Posner, Snyder, & Davidson, 1980). Errors in cuing tasks are often correct reports of items adjacent to the target (Mewhort, Campbell, Marchetti, & Campbell, 1981). Perhaps the strongest evidence for the necessity of selection by location is Nissen's (1985) finding that report of an object's attributes is contingent on the ability to locate the object. Attribute report is above chance if location reports are correct but at chance if location reports are not correct. Monheit and Johnston (1994) criticized Nissen's experiments, but van der Velde and van der Heijden (1997) rebutted their criticisms convincingly. Attribute report does seem contingent on localization, especially if the attribute is complex. There is some controversy remaining over the necessity of spatial attention for encoding simple features (M. Green, 1991), but it seems quite clear that spatial attention is necessary for encoding whole words, especially when there are competing words in the display (see, e.g., Brown, Roos-Gilbert, & Carr, 1995; Carr, 1992; McCann, Folk, & Johnston, 1992).

The theories of visual spatial attention and the data on the importance of location information lead us to predict that subjects must attend to location in tasks that require visual spatial attention. The attention hypothesis, derived from the instance theory of automaticity, leads us to predict that location information will be encoded into memory during automatization.

Obligatory Encoding of Location Information

Obligatory encoding of location information has been an important theme in memory research for the past 20 years. There is abundant evidence that subjects encode location information under incidental learning conditions (e.g., Acredolo, Pick, & Olsen, 1975; Mandler, Seegmiller, & Day, 1977; McCormack, 1982; Naveh-Benjamin, 1987, 1988; Park, Puglisi, & Lutz, 1982; von Wright, Gebhard, & Karttunen, 1975; Zechmeister, McKillip, Pasko, & Bespalec, 1975), which is consistent with the attention hypothesis, but there is controversy over the degree to which the learning was incidental. The literature shows that encoding was affected by subjects' strategies and intentions (see, e.g., Greene, 1984, 1986; Naveh-Benjamin & Jonides, 1986) and suffered interference from demanding concurrent tasks (Naveh-Benjamin, 1987, 1988; Naveh-Benjamin & Jonides, 1986). These effects are consistent with the attention hypothesis as well: If encoding of location depends on attention, then memory for location should be affected by manipulations of attention. Strategies and intentions change the way people attend, and so should affect what they remember. Concurrent tasks disrupt attention and so should disrupt memory.[2]

[2]The controversy surrounding the extent to which location encoding is incidental focuses on Hasher and Zacks' (1979, 1984) claims about the automaticity of encoding. Hasher and Zacks' claims can be interpreted in two ways. Under one interpretation, frequency and location information are encoded by special-purpose processors that are automatic in the sense that they are independent of attention. This interpretation is challenged by evidence that memory for frequency and location information is affected by strategy and intention and disrupted by a difficult concurrent task (Greene, 1984, 1986; Naveh-Benjamin, 1987, 1988; Naveh-Benjamin & Jonides, 1986). Under the other interpretation, frequency and location information are encoded as a side effect of

This literature on incidental memory for location may not be directly relevant to the instance theory. That literature addresses explicit memory—recognition and recall—whereas the instance theory and the attention hypothesis primarily address implicit memory—improvements in performance that result from repetition. The memory literature abounds with dissociations between implicit and explicit memory (for reviews, see Hintzman, 1990; Roediger, 1990), and obligatory encoding of location may be another phenomenon that dissociates. Consequently, it is important to look for evidence of obligatory encoding of location in implicit memory tests in tasks more like those in the automaticity literature.

There is some evidence of obligatory encoding of location information in visual search tasks. Miller (1988) had subjects search for target letters in four-letter displays. One kind of target, the *inducing target,* occurred in one position more often than 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. However, the advantage was greater for the inducing target than for the test target, which suggested that subjects associated particular targets with particular positions, as the attention hypothesis would predict.

Subsequently, Treisman, Vieira, and Hayes (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. Their results were consistent with the attention hypothesis (as they noted).

The experiments of Miller (1988) and Treisman et al. (1992) are encouraging, but it is not clear whether their results would generalize to the kinds of displays we used in our previous tests of the attention hypothesis (e.g., Boronat & Logan, 1997; Logan & Etherton, 1994; Logan et al., 1996). Our displays were simpler perceptually and more complex conceptually: We displayed two words, one above the other, and asked subjects to decide whether one of the words was a member of a target category, like *metals*. We kept the locations of targets, nontargets, and distractors consistent throughout training and transfer. It is possible that some of the learning we observed was due to obligatory encoding of consistent location information. We have no way of knowing that without further experiments that vary location and look for transfer costs.

The Experiments

We performed six experiments to test the obligatory 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., 1996), requiring subjects to search through one- or 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.

Automatic Encoding of Location Information

The series began with a straightforward attempt to test for encoding of location information under conditions that were a direct replication of the procedure in our previous category search experiments. Two words were presented one above the other in the center of a screen, and subjects decided whether one of them belonged to the target category (e.g., *metals*). Word location was constant throughout training and varied in transfer. Surprisingly, subjects were not sensitive to changes in location information at transfer, disconfirming the attention hypothesis, the obligatory encoding assumption, and the instance theory itself. An alternative hypothesis, suggested by the memory literature, was that subjects encoded location information just as the instance theory predicts, but they did not retrieve it in the transfer task. The remaining experiments examined three interpretations of this *retrieval-failure* hypothesis.

The second experiment tested the retrieval-failure hypothesis by examining a different retrieval task, explicit recognition of the words' locations. Subjects were trained on the same category search task as in Experiment 1, but transferred to a recognition memory task in which they judged whether or not the words changed location. Subjects were insensitive to changes in location on the explicit recognition test, contrary to the instance theory and contrary to the

attending (also see Barsalou, 1995). They are encoded automatically in the sense that encoding does not require further processing beyond attending. This interpretation is not challenged by evidence that memory for frequency and location information is affected by strategy and intention and disrupted by concurrent tasks. In fact, one could construe those data as evidence that supports this interpretation: If encoding of frequency and location is dependent on attention, then memory for frequency and location should be affected by manipulations of attention. Strategies and intentions change the way subjects attend, and so should affect what they remember. Concurrent tasks disrupt attention, and so should disrupt memory. The attention hypothesis and the instance theory endorse the second interpretation of Hasher and Zacks' position (also see Barsalou, 1995). The second interpretation is essentially the same as the obligatory encoding assumption. Thus, the evidence that strategies, intentions, and concurrent tasks affect memory for location information does not challenge the attention hypothesis. Indeed, it supports it.

memory literature, reviewed above, that showed strong sensitivity to location information in other explicit tests.

Experiments 3 and 4 tested a *cue-overload* interpretation of the retrieval-failure hypothesis (M. J. Watkins, 1979). Location may not have had an impact in Experiments 1 and 2 because there were so many words and only two locations. Location may not have been a very effective retrieval cue. Experiments 3 and 4 addressed this possibility by presenting single words in 16 different locations, reducing the word-to-location ratio from 32:1 to 2:1. Experiment 3 tested implicit memory, using the category search task, and Experiment 4 tested explicit memory, using the recognition task. Both memory tests showed a sensitivity to location change, confirming the cue-overload interpretation.

Experiments 5 and 6 tested an attentional overload interpretation of the lack of sensitivity to location observed in Experiments 1 and 2. Experiments 1 and 2 presented two words and found no sensitivity to location change; Experiments 3 and 4 presented one word and found significant sensitivity. The load on attention imposed by the second word may have impaired encoding or retrieval or both. Experiments 5 and 6 tested this hypothesis by presenting two words in 16 locations. If attentional load were the important factor, there should be no sensitivity to location change—the results should replicate Experiments 1 and 2. If cue overload were the important factor, there should be sensitivity to location change—the results should replicate Experiments 3 and 4.

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; Lassaline & Logan, 1993; 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), I did not test for automatization as rigorously as they did. I defined automatization in terms of a power-function reduction in reaction time. I did not test for a reduction in load effects or dual-task interference with practice.

Facilitation and Interference in Transfer Tests

The logic of the present and prior tests of the attention hypothesis involves using transfer tests to determine what was encoded and what was retrieved. Stimulus attributes are held constant during training and then changed at transfer. If those attributes were encoded during automatization and retrieved to support automatic performance, then transfer performance should be worse when the attributes change. Transfer costs may arise for two reasons. First, the changed attributes may be less effective as retrieval cues, so that memory traces that supported automatic performance are no longer retrieved. Thus, one explanation of transfer cost is the absence of facilitation from traces that can no longer be retrieved. Second, the changed attributes may retrieve traces that suggest different interpretations or different responses to the current stimulus that lead subjects to make an inappropriate response; changed attributes may retrieve traces that interfere with current responding.

Either interpretation is consistent with the attention hypothesis and with the instance theory, construed broadly. However, the instance theory, interpreted strictly, is more comfortable with the first interpretation than with the second, because it has no mechanism for resolving interference. The instance theory assumes a simple race model, in which performance is determined by the first trace to be retrieved. If that trace leads to the wrong response, subjects will make an error; interference will inflate error rate without affecting reaction time. Nosofsky and Palmeri (1997; Palmeri, 1997) generalized the instance theory from a simple race to a random walk model, which may be construed as a relay race in which several runners must finish before a response occurs.[3] Their version of the instance theory is able to

[3]Nosofsky and Palmeri's (1997; Palmeri, 1997) random walk model assumes the same retrieval process as the original instance theory (Logan, 1988). The response generation process is different. The random walk model assumes that traces are accumulated and a response occurs when the number of traces that favor one response exceeds the number of traces that favor another by a criterion, K. The random walk model accounts for interference effects on reaction time, because retrieval of traces that favor the wrong response will increase the time required to accumulate K more traces that favor the right response. For example, if $K = 3$ and there is no interference, then a correct response can occur after three correct traces are retrieved. However, if one interfering trace is retrieved, then a correct response cannot occur until four correct traces are retrieved; if two interfering traces are retrieved, then a correct response cannot occur until five correct traces have been retrieved; and so on. It takes more time to retrieve four correct traces than three, so retrieval of interfering traces will increase reaction time. Note that when $K = 1$, the random walk model is a

Table 1
Means and Standard Deviations of Measures of Word Frequency, Frequency of Mention, Prototypicality, and Word Length for the 16 Words in Each Category

	Metals		Countries		Vegetables		Furniture	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
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 Kučera and Francis (1967). [b]From Battig and Montague (1969). [c]From Uyeda and Mandler (1980).

account for interference effects on reaction time as well as accuracy.

The attention hypothesis is relatively neutral on the issue of facilitation versus interference. It addresses what is encoded and what is retrieved, not how the things that are retrieved are used to generate responses. The number of traces that must be retrieved before a response is generated is logically separate from the factors (attention) that determine retrieval in the first place. I will not distinguish between facilitatory and inhibitory interpretations of the transfer effects in the present experiments, and thus, I will not distinguish between the original instance theory and Nosofsky and Palmeri's (1997; Palmeri, 1997) generalization of it.

Experiment 1

Subjects performed the category search task throughout training and transfer, seeing two words, one above the other, in the center of the screen on each trial. At transfer, each word pair was presented twice, once with the words in the original locations and once with them in the opposite locations. The purpose of the experiment was to see whether subjects would be sensitive to the change in location, responding more quickly to same-location pairs than to different-location pairs. The attention literature suggests that subjects will attend to location, so the instance theory predicts they will learn it and be sensitive to location changes at transfer. This prediction stems from the core assumptions of the instance theory. Failure to confirm it can falsify the instance theory.

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 (1969) norms, prototypicality in the Uyeda and Mandler (1980) norms, word frequency in the Kučera 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 0.48 degrees of visual angle in height and a minimum of 0.76 degrees and a maximum of 2.29 degrees 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 degrees of visual angle horizontally and 1.72 degrees 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 1,000 ms. Then the screen went blank for 2,000 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 in each block. A different random pairing was constructed for each subject.

There were two basic trial types, target present and target absent,

simple race model, in which the response is determined by the first trace that is retrieved. Thus, the original instance theory is a special case of Nosofsky and Palmeri's generalized theory.

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 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 were two transfer blocks of 32 trials in which each pair was presented twice, once with the words in the same locations they appeared in during training and once with the words in the opposite locations.

Before the training phase began, subjects were given written instructions that described the category search 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 training phase began. Subjects were allowed brief rests every 128 trials (4 blocks). The last rest was just before the transfer trials. After the break before the transfer trials, subjects were told to continue with the category search task. They were not told that some of the words would change their locations.

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 Panel A of Figure 1. Reaction time decreased and accuracy increased with practice. The speedup in reaction time was negatively accelerated, with the largest gains in the early trials, which is characteristic of the power-function speedup that is the hallmark of automatization (Logan, 1992; Newell & Rosenbloom, 1981). Power functions were fitted to the reaction time data. The lines in Figure 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) analyses of variance (ANOVAs), using $p < .05$ as the significance level. The ANOVA on reaction times found significant main

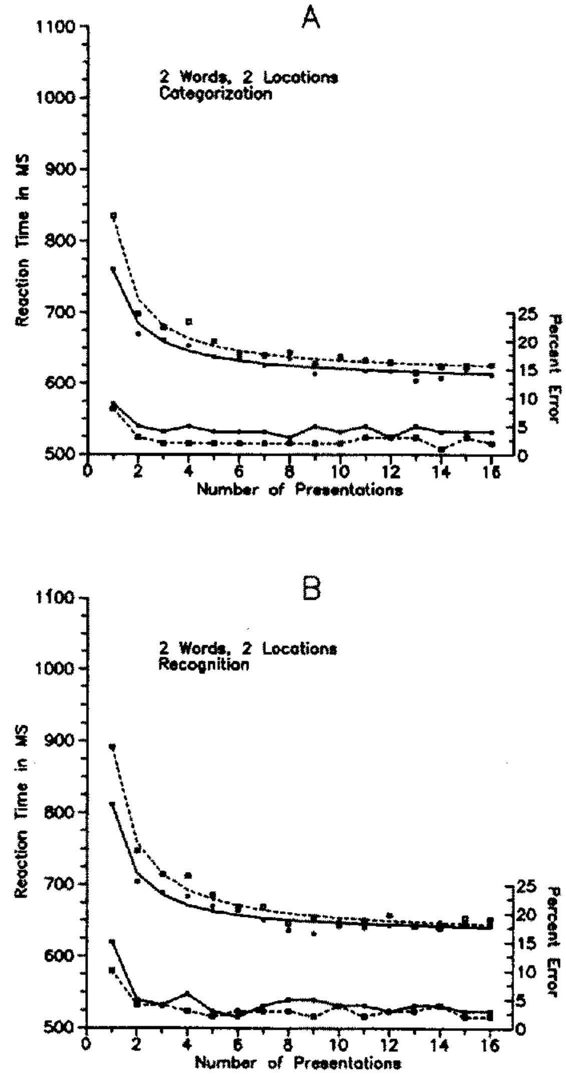

Figure 1. Mean reaction times (top two lines, left-hand *y*-axis) and error rates (bottom two lines, right-hand *y*-axis) for target-present (filled squares and solid lines) and target-absent (open squares and dotted lines) responses from the training phase of Experiment 1 (Panel A) and Experiment 2 (Panel B) as a function of number of presentations (for the reaction times, the lines represent the best-fitting power function and the squares represent the observed data).

effects of target presence, $F(1, 31) = 21.39$, $MSE = 3{,}928.42$, and practice block, $F(15, 465) = 49.09$, $MSE = 2{,}686.00$, and a significant interaction between target presence and practice, $F(15, 465) = 4.63$, $MSE = 1{,}023.41$.

In the ANOVAs on the accuracy scores (percentage of correct responses) the main effect of practice block was significant, $F(15, 465) = 6.41$, $MSE = 19.27$, as was the main effect of target presence, $F(1, 31) = 6.28$, $MSE = 136.25$. No other effects were significant.

Transfer. Mean reaction times and percent correct scores for same- and different-location trials in the transfer blocks for target-present and target-absent responses in Experi-

Table 2
Power Function Fits to Mean Reaction Times From Experiments 1–6

Experiment	r^2	*rmsd*	*a*	*b*	$-c$
1					
Present	.949	8.30	601	155	0.900
Absent	.969	9.05	614	217	1.059
2					
Present	.963	8.23	633	177	1.092
Absent	.981	8.45	629	261	1.017
3					
Present	.862	6.43	710	67	1.715
Absent	.904	5.97	711	76	1.531
4					
Present	.782	6.20	698	49	2.629
Absent	.814	7.13	704	62	1.657
5					
Present	.969	7.13	749	215	0.447
Absent	.957	10.69	738	304	0.357
6					
Present	.968	7.49	705	221	0.451
Absent	.982	8.07	676	344	0.377

Note. 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.

ment 1 are presented in Table 3. Reaction time was not affected by changing the locations of the words in the pairs. Mean reaction time for same-location pairs was 635 ms; mean reaction time for different-location pairs was also 635 ms. Accuracy was barely affected by changing the locations of the words, dropping by 0.5%. These data suggest either that information about the location of targets, nontargets, and distractors was not encoded in the memory trace or that the retrieval task was not sensitive to it.

The mean reaction times and percent correct scores were analyzed in 2 (location same vs. different) × 2 (target present vs. absent) ANOVAs. No effects were significant in the reaction time ANOVA. In the accuracy ANOVA, only the effect of target presence was significant, $F(1, 31) = 9.04$, $MSE = 27.08$.

Discussion

The power-function speedup suggested that some degree of automatization occurred during training (for converging evidence, see Boronat & Logan, 1997; Logan & Etherton, 1994). The transfer results suggest that location information was not encoded, which is bad news for the instance theory of automaticity. The assumptions that underlie the attention hypothesis are the most basic ones in the instance theory, so falsification of the attention hypothesis amounts to falsification of the theory. The successes of the instance theory in the past led me to search for alternative interpretations that might render the results less damaging.

One possibility is that subjects did not attend to location. However, that is contrary to the task instructions and to the large literature on visual attention, which suggests that attention to location is obligatory. Another possibility is that location may have been encoded, as the attention literature and the instance theory would predict, but it was not available or not accessible to the retrieval processes at the transfer test. In other words, the results reflect a retrieval failure rather than an encoding failure. The remaining experiments tested three versions of the retrieval-failure hypothesis: sensitivity, cue-overload, and attentional limitations.

Experiment 2

The retrieval processes at work in the category search transfer task of Experiment 1 may not have been very

Table 3
Mean Reaction Times and Percentage of Correct Responses for the Last Training Block and for Same- and Different-Location Trials in the Transfer Blocks of Experiments 1, 3, and 5

	Last		Target: Same		Target: Different		Cost		
Condition	*M*	% correct	*M*	% correct	*M*	% correct	*M*	% correct	Target
Experiment 1									
2 words	614	94	631	96	636	95	5	1	Present
2 locations	626	98	639	98	634	98	−5	0	Absent
Experiment 3									
1 word	717	95	700	96	713	95	13	1	Present
16 locations	708	96	695	93	712	96	17	−3	Absent
Experiment 5									
2 words	816	93	807	95	839	91	32	4	Present
16 locations	858	97	849	97	878	96	29	1	Absent

Note. Last = last training block; Same = same location in transfer as in training; Different = different location in transfer than in training; Cost = different–same.

sensitive to the presence of location information in the memory traces (see Logan et al., 1996). Category search places a premium on the speed of retrieval: Subjects can respond as soon as they retrieve the first trace. Slower traces retrieved after that will have little impact on the response. Perhaps the parts of the trace that contain location information were not retrieved very quickly. A different retrieval task that places less emphasis on speed may be sensitive to traces that take longer to retrieve. Moreover, a task that explicitly asks for judgments about retrieved location information should be more sensitive to those parts of the trace that contain it.

Experiment 2 used an explicit recognition memory test at transfer to see whether it was more sensitive to stored location information than the category search task of Experiment 1. The training phase was exactly the same as in Experiment 1. The transfer phase used the same stimulus materials and presentation conditions as Experiment 1—each pair was presented twice, once with the words in the same locations as in training and once with the words in opposite locations—but differed in the instructions to the subjects. The recognition memory task asked them to judge explicitly whether the words were in same or different locations.

The retrieval-sensitivity version of the retrieval-failure hypothesis predicts above-chance sensitivity to location change on the recognition test, suggesting that location information was encoded but the category-search retrieval task of Experiment 1 was not sensitive to it. Chance-level sensitivity to location change would suggest that location information was not encoded during training and the instance theory and the memory literature are wrong, or that retrieval failed for some other reason.

Method

Subjects. The subjects were 32 volunteers from an introductory psychology course. None served in Experiment 1.

Apparatus and stimuli. The apparatus and stimuli were the same as in Experiment 1 in all respects.

Procedure. The procedure was the same as in Experiment 1 up to the transfer test. In the transfer test, temporal and spatial parameters and the pairing and positioning of words were the same as in Experiment 1. The only difference was in the transfer-task instructions. Subjects in Experiment 2 were told that they would see the word pairs from the training phase, and that the words would appear in the same locations as in training for half of the pairs, but in opposite locations for the other half. Their task was to indicate whether the words in each pair appeared in the same or the opposite locations they appeared in during training.

Results

Training. The mean reaction times for target-present and target-absent responses and the mean error rates in the 16 training blocks were presented earlier in Panel B of Figure 1. Reaction time decreased and accuracy increased with practice. The speedup was characteristic of the power-function speedup (Logan, 1992; Newell & Rosenbloom, 1981). Power functions were fitted to the reaction time data. The lines in Figure 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. The fits were good.

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, $F(1, 31) = 7.17$, $MSE = 9{,}874.58$, and practice block, $F(12, 465) = 35.85$, $MSE = 5{,}124.00$, and a significant interaction between them, $F(15, 465) = 6.44$, $MSE = 1{,}183.49$. In the accuracy ANOVA, only the main effect of practice block was significant, $F(15, 465) = 10.83$, $MSE = 32.27$.

Transfer. The mean hit and false alarm rates for recognition judgments for target-present and target-absent stimuli in Experiment 2 are presented in Table 4. Hit rate was lower than false alarm rate for both target-present and target-absent pairs, suggesting that subjects had no sensitivity to the changes in the words' locations. A one-way ANOVA (target present vs. target absent) on hit rates minus false alarm rates revealed no significant difference between target-present and target-absent stimuli, $F < 1.0$, and no significant difference between the observed values and the chance value of zero, $LSD_{.05} = 0.0713$.

The same data were analyzed using the d' statistic from signal detection theory (D. M. Green & Swets, 1965; Lockhart & Murdock, 1970). The signal-detection analyses led to the same conclusion: d's, also presented in Table 4, were slightly negative. The d' values for target-present and target-absent pairs were not significantly different from each other, $F < 1.0$, or significantly different from the chance value of zero, $LSD_{.05} = 0.22$.

Discussion

The training data replicated Experiment 1, showing a power-function speedup that is characteristic of automatization (Logan, 1992; Newell & Rosenbloom, 1981). The transfer data replicated Experiment 1 as well, showing no sensitivity to changes in location information on a recognition memory test. The recognition data suggest two interpre-

Table 4
Mean Hit Rates, False Alarm (FA) Rates, and d' Values for Target-Present and Target-Absent Stimuli in Recognition Transfer Tests in Experiments 2, 4, and 6

Condition	Target present Hit	FA	d'	Target absent Hit	FA	d'
	Experiment 2					
2 words, 2 locations	.53	.55	−0.07	.61	.61	−0.06
	Experiment 4					
1 word, 16 locations	.69	.36	0.96	.67	.41	0.72
	Experiment 6					
2 words, 16 locations	.75	.37	1.19	.73	.50	0.64

tations: Either location was not encoded during training, which is contrary to the instance theory and contrary to the large literature on incidental memory for location (e.g., Acredolo et al., 1975; Mandler et al., 1977; McCormack, 1982; Naveh-Benjamin, 1987, 1988; Park et al., 1982; von Wright et al., 1975; Zechmeister et al., 1975), or location information was encoded but not retrieved.

Experiment 2 was designed to test a retrieval-sensitivity version of the retrieval-failure hypothesis, asking subjects about memory for location explicitly and giving them more time to respond. Subjects took more than twice as long on the recognition memory test (M = 1,484 ms) as subjects in Experiment 1 took on the category search transfer task (M = 635 ms). Nevertheless, they could not recognize changes in location even though they were set to look for them. Thus, differential retrieval sensitivity cannot account for the null results of Experiment 1.

The next two experiments tested a cue-overload interpretation of the retrieval-failure hypothesis (Mueller & Watkins, 1977; M. J. Watkins, 1979; M. J. Watkins & Watkins, 1976; O. C. Watkins & Watkins, 1975). Experiments 1 and 2 presented 64 words in only two locations. Thus, 32 words were associated with each location. With such a high ratio of words to locations, location would not be a very effective retrieval cue. The probability of retrieving an instance of a prior presentation of a given word would not be much higher than the probability of retrieving prior representations of other words, and that would depress performance on both the implicit and explicit memory tests. Indeed, most of the studies that examined obligatory encoding of location with explicit memory tests used item-to-location ratios that were much lower than the 32:1 ratio we used (e.g., Naveh-Benjamin, 1987, 1988, used a 1:1 ratio: 20 pictures and 20 locations).

Experiments 3 and 4: One Word and 16 Locations

Experiments 3 and 4 were conducted to test a cue-overload version of the retrieval-failure hypothesis. Subjects in Experiments 1 and 2 may have encoded location during training but were not able to retrieve things associated with location at transfer because so many words were associated with so few positions. Experiments 3 and 4 were conceptual replications of Experiments 1 and 2 with fewer words displayed in more locations: Only one word was presented on each trial, and that word could appear in 1 of 16 locations. The lower ratio of words to location (2:1 vs. 32:1) should be reduce cue overload in both implicit and explicit tests. If cue overload was responsible for the null sensitivity to location change in Experiments 1 and 2, subjects should show above-chance sensitivity in Experiments 3 and 4.

The training task for Experiments 3 and 4 was the same as in Experiments 1 and 2. Subjects decided whether the word was a member of a target category. The transfer tasks were the same as in Experiments 1 and 2 as well. Subjects in Experiment 3 continued the category search task they performed in training. Differences in reaction time to same-location and different-location words would indicate, implicitly, memory for location information. Subjects in Experiment 4 performed a recognition task at transfer, deciding whether each word appeared in the same location or a different location during training. Above-chance recognition accuracy would indicate explicit memory for location information.

Method

Subjects. The subjects were 60 volunteers from an introductory psychology course. Half served in Experiment 3 and half served in Experiment 4. None had served in the previous experiments.

Apparatus and stimuli. The apparatus and stimuli were the same as those used in Experiment 1. There were three differences: First, the fixation and orienting display contained a plus sign (+) centered in the screen (in column 12, row 40 of the IBM text screen) instead of two flanking lines. Second, one word rather than two appeared on each trial. And third, that word appeared in 1 of 16 possible locations instead of 1 of 2. The 16 locations comprised an invisible 4 × 4 grid centered on the screen with 3.2 cm horizontally and vertically between adjacent positions. Words appeared left-justified in this grid, with their initial letters centered on the grid position. The grid was 9.6 × 9.6 cm, spanning 9.09 × 9.09 degrees of visual angle when viewed at a distance of 60 cm. In terms of IBM text-screen coordinates, the columns of the grid were 20, 30, 40, and 50 and the rows were 6, 10, 14, and 18.

Procedure. The procedure was the same as in Experiments 1 and 2, except that subjects saw only one word each trial. There were 16 training blocks of 32 trials, in which 16 targets and 16 nontargets each appeared (alone) once. There were two 32-trial transfer blocks, in which each word appeared in the position it appeared in during training or in another location randomly selected from the 15 alternatives.

We attempted to counterbalance assignment to target and nontarget categories and assignment of decisions to response keys. In each experiment, half of the subjects used one of the mappings from Experiments 1 and 2 to report their decisions and half subjects used the other. However, the 12 possible assignments of the four categories to target and nontarget roles were not assigned equally to all subjects. Three subjects got 6 of the possible assignments and 2 got the other 6. Response-key assignment and category assignment were completely counterbalanced in 24 of the 30 subjects in each experiment, and the results from those 24 subjects appeared substantially the same as the results from all 30. We could have completely counterbalanced the experiments by stopping at 24 subjects or by running 48 subjects. Instead, we chose to keep the total number of subjects in each experiment comparable to the total numbers in the other experiments (30 instead of 32) to keep the standard errors of measurement roughly the same across experiments.

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 Figure 2. The data from Experiment 3 appear in Panel A and the data from Experiment 4 appear in Panel B. Reaction time decreased and accuracy increased with practice in both experiments. Power functions were fitted to the reaction time data. The lines in Figure 2 represent the fitted functions; the points represent the observed data. Measures of goodness of fit and the

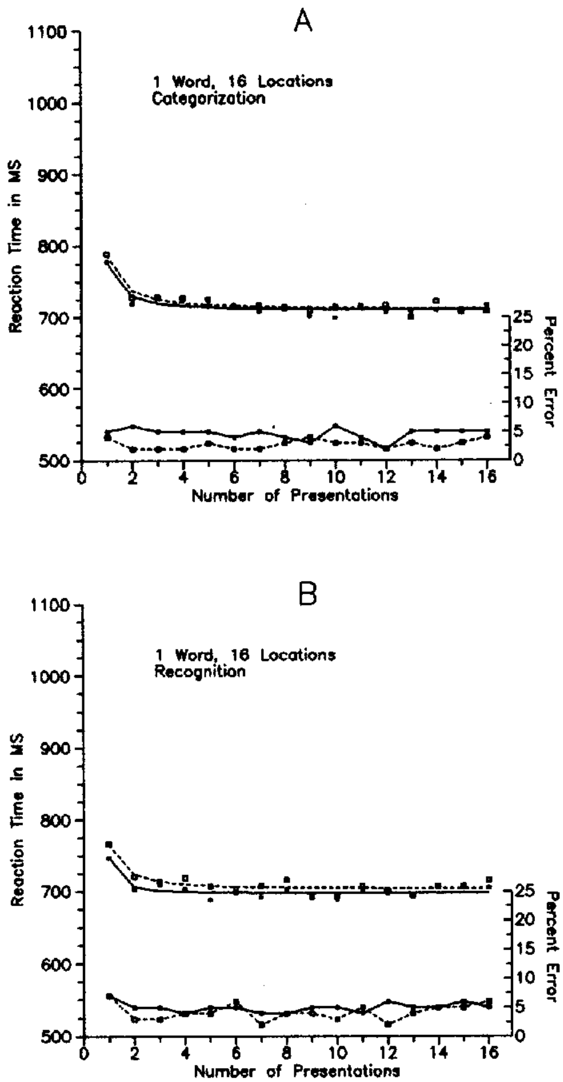

Figure 2. Mean reaction times (top two lines, left-hand *y*-axis) and error rates (bottom two lines, right-hand *y*-axis) for target-present (filled squares and solid lines) and target-absent (open squares and dotted lines) responses from the training phase of Experiment 3 (Panel A) and Experiment 4 (Panel B) as a function of number of presentations (for the reaction times, the lines represent the best-fitting power function and the squares represent the observed data).

parameters of fitted functions are presented in Table 2. Again, the fits were good.

The learning curves were shallower than the ones in Experiments 1 and 2, and they asymptoted at higher values. These differences may stem from two factors: First, there was only one word per display in Experiments 3 and 4, whereas there were two per display in Experiments 1 and 2. Previous research with this paradigm that compared learning with one versus two relevant items showed shallower learning curves for one item than for two (Boronat & Logan, 1997; Logan & Etherton, 1994; also see Logan et al., 1996). Second, the displays subtended a much larger visual angle in Experiments 3 and 4 than in Experiments 1 and 2. The words were farther in the periphery, where acuity is low, and subjects may have moved their eyes to the words before processing them, on some of the trials, at least. The higher asymptote may reflect the additional time required for these eye movements, when they occurred.

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 for practice block, Experiment 3: $F(15, 435) = 10.86$, $MSE = 1{,}900.88$; Experiment 4: $F(15, 435) = 5.20$, $MSE = 2{,}642.62$. No other effects were significant. In the accuracy ANOVAs, the main effect of target presence was significant in Experiment 3, $F(1, 29) = 5.78$, $MSE = 132.13$, and the main effect of practice block was significant in Experiment 4, $F(15, 435) = 2.61$, $MSE = 23.55$. No other effects were significant.

Transfer: Implicit test (Experiment 3). Mean reaction times and percent correct scores for same- and different-location trials in the transfer blocks for target-present and target-absent responses in Experiment 3 are presented in Table 3. In the transfer blocks, mean reaction time was 15 ms longer for different-location words than for same-location words, and accuracy was 1% lower. These data suggest that information about the location of targets and nontargets was encoded in the memory trace and was available to the implicit-memory retrieval task.

The mean reaction times and percent correct scores were analyzed in 2 (location same vs. different) × 2 (target present vs. absent) ANOVAs. The effect of location change was significant in the reaction time ANOVA, $F(1, 29) = 9.95$, $MSE = 675.41$. No effects were significant in the accuracy ANOVA.

Transfer: Explicit test (Experiment 4). The mean hit and false alarm rates for recognition judgments for target-present and target-absent stimuli in Experiment 4 are presented in Table 4. Hit rate was about 30% higher than false alarm rate, averaged over target-present and target-absent pairs, suggesting that subjects had some sensitivity to the changes in the words' locations. A one-way ANOVA (target present vs. target absent) on hit rates minus false alarm rates revealed a marginally significant main effect of target presence, $F(1, 29) = 3.54$, $p < .07$, $MSE = 212.46$. The difference between the observed values and the chance value of zero was significant, $LSD_{.05} = 0.0744$.

An analysis using the d' statistic from signal detection theory led to the same conclusion: The main effect of target presence was marginally significant, $F(1, 29) = 4.01$, $p < .06$, $MSE = 0.215$; both values were significantly different from the chance value of zero, $LSD_{.05} = 0.237$. The d' values appear in Table 4.

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 (also see Boronat & Logan, 1997; Logan & Etherton, 1994). Subjects displayed some sensitivity to changes in location at transfer, in both implicit and explicit tests of memory. This suggests that subjects encoded location information during training, which is consistent with the attention hypothesis and the instance theory. Moreover, the memory performance supports a cue-overload interpretation of the results of Experiments 1 and 2. According to the cue-overload hypothesis, subjects may have failed to retrieve associations involving location in Experiments 1 and 2 because so many words were associated with so few locations (word:location = 32:1). If cue overload was responsible for poor memory performance in those experiments, then reducing the item-to-location ratio in the present experiments to 2:1 should increase sensitivity to changes in location, and that is what was found. Thus, the results of Experiments 1 and 2 may not be inconsistent with the attention hypothesis and therefore may not falsify the instance theory. Subjects may have encoded location information but may have been unable to retrieve it due to cue overload.

Experiments 5 and 6: Two Words and 16 Locations

Experiments 3 and 4 differed from Experiments 1 and 2 in the number of words presented on each trial. The extra word in Experiments 1 and 2 may have imposed a load on attention that impaired encoding or retrieval or both (e.g., Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Jacoby, 1991). Experiments 5 and 6 were designed to distinguish between this *attention load* interpretation and the cue-overload interpretation given earlier.

Experiments 5 and 6 presented two words per trial, like Experiments 1 and 2, but distributed them over 16 locations, like Experiments 3 and 4, pitting cue overload against attention load. The item-to-location ratio was 4:1, which is much smaller than the 32:1 ratio in Experiments 1 and 2. If cue overload were responsible for the contrast between Experiments 1 and 2 and Experiments 3 and 4, subjects should show a sensitivity to location change similar to that in Experiments 3 and 4. However, if attention load were responsible for the contrast, then subjects should show a null sensitivity to location change, like subjects in Experiments 1 and 2.

Experiment 5 used the implicit test at transfer; Experiment 6 used the explicit recognition test. The attention load hypothesis applies primarily to the explicit memory test. There is some evidence that implicit memory tests are less susceptible to attention load effects (e.g., Jacoby, 1991; Jacoby, Woloshyn, & Kelley, 1989; Parkin, Reid, & Russo, 1990; but see Carrier, Pashler, & McFarland, 1994).

Method

Subjects. The subjects were 64 volunteers from an introductory psychology course. Thirty-two served in Experiment 5 and 32 served in Experiment 6. None had served in the previous experiments.

Apparatus and stimuli. The apparatus and stimuli were the same as those used in the previous experiments. The two words presented in each trial were chosen according to the constraints imposed in Experiments 1 and 2 (i.e., target-present displays consisted of one member of the target category paired with one member of either of two distractor categories; target-absent displays consisted of one member of the nontarget category paired with one member of one of the distractor categories). The two words appeared in 2 of 16 locations in an invisible 4 × 4 grid, as in Experiments 3 and 4. The main difference was that the horizontal extent of the grid was extended by two character spaces per position (from 10 to 12) so that adjacent words on the same line would not overlap (maximum word length was 11). The vertical dimensions of the grid were the same as in Experiments 3 and 4. The distance between columns increased from 3.2 to 3.9 cm, and the distance between the first and fourth column increased from 9.9 cm to 11.6 cm. Viewed at a distance of 60 cm, the horizontal distance subtended 10.9 degrees of visual angle.

Procedure. Subjects had 16 blocks of 32 training trials and 2 blocks of 32 transfer trials, in which the words were presented once in the same locations they appeared in during training and once in the opposite locations (i.e., locations switched, as in Experiments 1 and 2). Subjects in Experiment 5 performed the category search task throughout training and transfer; subjects in Experiment 6 performed category search in training and made recognition judgments in transfer.

Response-key assignment and category assignment were completely counterbalanced, as in Experiments 1 and 2.

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 Figure 3. The data from Experiment 5 are presented in Panel A and the data from Experiment 6 are presented in Panel B. 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 Figure 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 were longer in these experiments than in the previous ones because of the size of the viewing area—some words could appear far in the periphery and therefore require eye movements—and because two words were presented rather than one. Target-present responses were much faster than target-absent responses, and the difference persisted throughout practice even though it diminished somewhat. This difference may also reflect eye movements: Words were assigned to locations randomly, and some of the time the two words were quite far from each other. Subjects may have had to (or may have chosen to) move their eyes from one word to another when the words were far apart. This extra eye movement would be required on all target-absent trials, because the first word fixated (or examined) would never be the target. The extra eye movement would be required only on about half of the target-present trials, because the first word fixated (or examined) would be the target about half of the time, and subjects could respond right away, without examining the other word (i.e., they could adopt a self-terminating search strategy).

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, Experiment 5: $F(1, 31) = 57.43$, $MSE =$

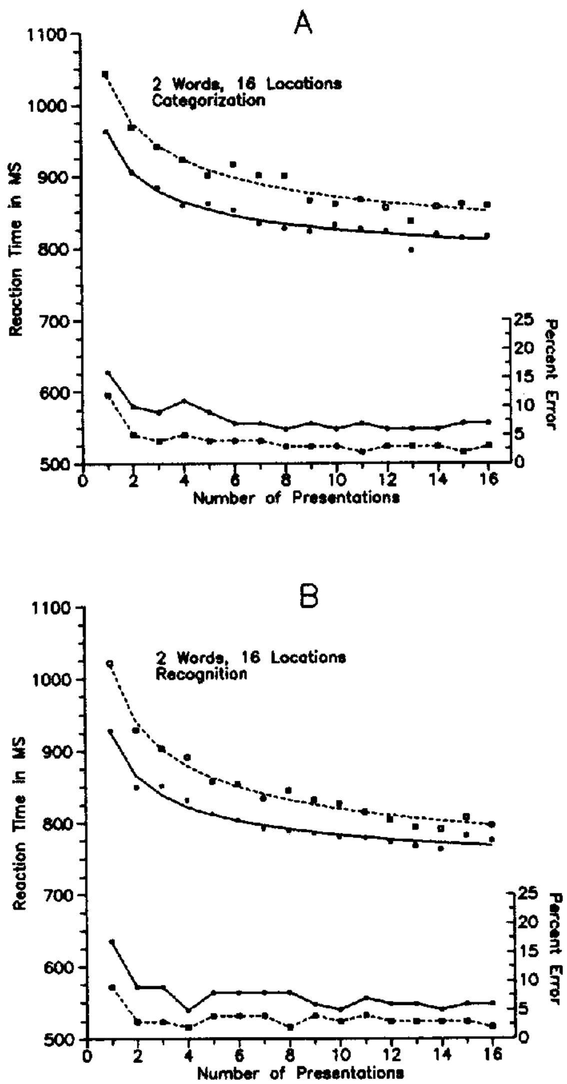

Figure 3. Mean reaction times (top two lines, left-hand *y*-axis) and error rates (bottom two lines, right-hand *y*-axis) for target-present (filled squares and solid lines) and target-absent (open squares and dotted lines) responses from the training phase of Experiment 5 (Panel A) and Experiment 6 (Panel B) as a function of number of presentations (for the reaction times, the lines represent the best-fitting power function and the squares represent the observed data).

11,849.75; Experiment 6: $F(1, 31) = 53.00$, MSE = 10,237.18, and practice block; Experiment 5: $F(15, 465)$ = 29.06, MSE = 49.46.96; Experiment 6: $F(15, 465) = 47.20$, MSE = 3,685.22, and a significant interaction between target presence and practice, Experiment 5: $F(15, 465)$ = 2.40, MSE = 1,654.12; Experiment 6: $F(15, 465) = 4.47$, MSE = 1,410.48.

The ANOVA on the accuracy scores revealed a significant main effect of target presence, Experiment 5: $F(1, 31)$ = 14.16, $MSE = 326.90$; Experiment 6: $F(1, 31) = 73.51$, $MSE = 54.63$, and a significant main effect of practice block, Experiment 5: $F(15, 465) = 13.25$, $MSE = 30.59$; Experiment 6: $F(15, 465) = 11.28$, $MSE = 25.47$. The interaction between target presence and practice block was marginally significant in Experiment 6, $F(15, 465) = 1.67$, $p < .06$, $MSE = 28.05$.

Transfer: Implicit test (Experiment 5). Mean reaction times and percent correct scores for same- and different-location trials in the transfer blocks for target-present and target-absent responses in Experiment 5 are presented in Table 3. Mean reaction time was 31 ms longer for different-location words than for same-location words, and accuracy was 2% lower. These data suggest that information about the location of targets and nontargets was encoded in the memory trace and was available to the implicit-memory retrieval task.

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 target presence was significant, $F(1, 31)$ = 16.25, MSE = 2,943.43, as was the main effect of location change, $F(1, 31) = 14.70$, MSE = 2,190.21. In the accuracy ANOVA, the main effect of target presence, $F(1, 31) = 8.44$, $MSE = 59.25$, the main effect of location change, $F(1, 31)$ = 5.25, $MSE = 24.02$, and the interaction between target presence and location change, $F(1, 31) = 8.51$, $MSE = 9.74$, were significant.

Transfer: Explicit test (Experiment 6). The mean hit and false alarm rates for recognition judgments for target-present and target-absent stimuli in Experiment 6 are presented in Table 4. Hit rate was 31% higher than false alarm rate, averaged over target-present and target-absent pairs, suggesting that subjects were sensitive to the changes in the words' locations. A one-way ANOVA (target present vs. target absent) on hit rates minus false alarm rates revealed a significant main effect of target presence, $F(1, 31)$ = 13.56, $MSE = 266.96$, and the difference between the observed values and the chance value of zero was significant, $LSD_{.05} = 0.0834$.

A signal detection analysis led to the same conclusion. The d' values also appear in Table 4. There was a significant main effect of target presence, $F(1, 31) = 11.68$, MSE = 0.416, and each value was significantly different from the chance value of zero, $LSD_{.05} = 0.329$.

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). Subjects were sensitive to changes in location at transfer on both implicit and explicit memory tests, suggesting that location information had been encoded during training. These results are consistent with the attention hypothesis and the instance theory.

The results support a cue-overload interpretation of the contrast between Experiments 1 and 2 and Experiments 3 and 4 rather than an attention load interpretation. The number of locations, or the ratio of words to locations, seems to be more important than the number of words. Of course, this conclusion may be limited to the contrast between one and two words. When many more words appear on the screen, attention load may have a larger impact. To the extent that there was an attention load, the attention load affected both implicit and explicit memory tests, which is contrary to the idea that implicit memory tests are less susceptible to attention load effects (e.g., Jacoby, 1991; Jacoby et al., 1989; Parkin et al., 1990; but see Carrier et al., 1994).

Comparing Location Costs Between Experiments

The interpretation of the data depends on comparisons between experiments. To justify my conclusions, I did formal comparisons of location sensitivity across experiments. Reaction times from the implicit memory tests were analyzed in a 3 (Experiments: 1 vs. 3 vs. 5) × 2 (target present or absent) × 2 (location same or different) ANOVA, which revealed a significant main effect of experiments, $F(2, 91) = 42.38$, $MSE = 34{,}206.42$, a significant main effect of location change, $F(1, 91) = 16.09$, $MSE = 1{,}398.93$, and a significant interaction between them, $F(2, 91) = 5.84$, $MSE = 1{,}398.93$. The costs of changing location were compared across experiments with Fisher's LSD test, using the error term from the interaction between experiments and location change. By this comparison, the costs in Experiment 3 (one word, 16 locations) were significantly greater than the costs in Experiment 1 (one word, 2 locations), and the costs in Experiment 5 (two words, 16 locations) were significantly greater than the costs in Experiment 3 ($LSD_{.01} = 10$ ms).

The main effect of target presence, $F(1, 92) = 7.87$, $MSE = 1{,}904.20$, and the interaction between experiments and target presence, $F(2, 91) = 8.56$, $MSE = 1{,}904.20$, were also significant in the reaction time analysis. In an ANOVA with the same structure on the accuracy data, the experiments factor did not produce a significant main effect, and it did not interact with location change or target presence.

Hit rates minus false alarm rates and d's from the explicit memory tests were analyzed in 3 (Experiments: 2 vs. 4 vs. 6) × 2 (target present or absent) ANOVAs. The ANOVA on hits minus false alarms revealed a significant main effect of experiments, $F(2, 91) = 26.14$, $MSE = 805.54$, a significant main effect of target presence, $F(1, 91) = 10.19$, $MSE = 225.09$, and a significant interaction between them, $F(2, 91) = 4.66$, $MSE = 225.09$. Fisher's LSD test revealed a significant difference between Experiments 2 and 4 but no significant difference between Experiments 4 and 6 ($LSD_{.01} = 0.1101$).

The ANOVA on d's produced nearly identical results: The main effect of experiments was significant, $F(2, 91) = 22.48$, $MSE = 0.839$, as was the main effect of target presence, $F(1, 91) = 11.75$, $MSE = 0.270$, and the interaction between experiments and target presence, $F(2, 91) = 4.68$, $MSE = 0.270$. Fisher's LSD revealed a significant difference between Experiments 2 and 4 but no significant difference between Experiments 4 and 6 ($LSD_{.01} = 0.355$).

These analyses confirm our conclusions about between-experiment comparisons. Subjects were sensitive to changes in location in Experiments 3–6 but not in Experiments 1 and 2. These analyses also reveal associations and dissociations between the implicit and explicit memory tests. On the one hand, the two tests are associated because they both show greater sensitivity to location change in Experiments 3–6 than in Experiments 1 and 2. One interpretation of this association is that cue-overload effects occur in both implicit and explicit memory tests (also see M. J. Watkins, 1979).

On the other hand, implicit and explicit memory tests were dissociated in their response to Experiments 3 and 4 versus 5 and 6. The implicit memory test showed greater sensitivity to location change when two words appeared in 16 locations than when one word appeared in 16 locations, whereas the explicit memory test showed no difference in sensitivity depending on the number of words that appeared in 16 locations. I have no interpretation for this dissociation.

General Discussion

The experiments were designed to determine whether location information was encoded obligatorily during automatization, to test core assumptions of the instance theory of automaticity. Each experiment showed evidence of automatization, in that reaction time decreased as a power function of practice. The power-function speedup is not strong evidence of automatization by itself, 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 speedup in subjects from the same population. Thus, it seems reasonable to interpret the present power-function speedup as evidence for automatization.

Experiment 1 replicated the basic category search task we used in previous investigations of the attention hypothesis and, surprisingly, found no cost of changing location. Either location was not encoded, or it was encoded but not retrieved. The first interpretation is inconsistent with the attention literature, the memory literature, and the instance theory; the second is consistent with all of them, sparing the instance theory a fatal blow. The subsequent experiments tested three retrieval-failure interpretations of Experiment 1.

Experiment 2 tested the idea that the category search transfer task in Experiment 1 was not sufficiently sensitive to location information (e.g., Logan et al., 1996). Subjects were trained to perform category search and transferred to an explicit recognition memory task. Recognition performance showed no hint of sensitivity to location information. This suggests again that location information was not encoded or that it was encoded but not retrieved for some reason other than differential sensitivity.

Experiments 3 and 4 tested a cue-overload interpretation of the results of Experiments 1 and 2: Location may have been encoded in training but not retrieved in transfer because too many words (32) were associated with too few locations (2). Experiments 3 and 4 changed the ratio of words to locations from 16:1 to 2:1, presenting single words in 16 locations, and found significant sensitivity to location change on both implicit and explicit tests, corroborating the cue-overload interpretation of Experiments 1 and 2.

Experiments 5 and 6 contrasted an attention-load version of encoding- and retrieval-failure hypotheses with a cue-overload version of the retrieval-failure hypothesis. Two words were presented on each trial, as in Experiments 1 and 2, and they appeared in 16 locations, as in Experiments 3 and 4. If attention load was responsible for the difference between Experiments 1 and 2 and Experiments 3 and 4, then implicit and explicit memory should be as bad as in Experiments 1 and 2. If cue overload was responsible, then implicit and explicit memory should be as good as in Experiments 3 and 4. The results replicated Experiments 3 and 4, showing significant sensitivity to location change in both implicit and explicit tests, corroborating the cue-overload interpretation of the contrast between Experiments 1 and 2 and Experiments 3 and 4.

The Attention Hypothesis and the Instance Theory

On the balance, the results support the attention hypothesis, though the instance theory had a close call. The null sensitivity to location change in Experiment 1 is potentially fatal to the instance theory. The subsequent experiments support a retrieval-failure interpretation of Experiment 1, arguing that location information was encoded during training but not retrieved during transfer, and that interpretation can save the instance theory.

The retrieval-failure interpretation should not be viewed as a "patch" chosen arbitrarily to save the instance theory. Instead, it is an expression of the instance theory's fundamental precept, that automaticity is a memory phenomenon, governed by the theoretical and empirical principles that govern memory. Principles of attention, like obligatory attention to location, may explain what is learned during automatization, but principles of memory, like cue overload, explain how that learning is expressed at retrieval time in automatic performance and explicit memory tasks.

The present experiments were unlike our previous investigations of the attention hypothesis in that there were no tests in immediate performance to confirm the assumption that subjects attended to location. Instead, I relied on 15 years of theory and data in the attention literature. In addition, I relied on the results of the experiments to confirm my assumptions about attention to location. Thus, the results do double duty. On the one hand, they confirm the assumptions about how attention was deployed; on the other, they confirm the predictions about what was learned during automatization. It would have been better to have confirmed the assumptions and predictions separately, as we did in our previous experiments, but the results appear strong enough to do the double duty, replicating previous findings with simpler search tasks (i.e., Miller, 1988; Treisman et al., 1992). Moreover, the assumption of obligatory attention to location is strongly supported in the attention literature; much of the duty is already done.

Associative Bases of Automatic Category Search

The present experiments support another principle of memory that is fundamental to the instance theory: the assumption of *instance representation.* The results show that the memory traces that are acquired during automatization and retrieved during skilled performance contain information about the *co-occurrences* of different stimulus properties. In particular, spatial location appears to be associated with word identity. This is important, because representation of co-occurrence is a defining feature of instance representation (Barsalou, 1990; Logan & Etherton, 1994). Instances represent processing episodes that occur in a particular place at a particular time. Particular stimuli are processed in particular ways. Particular judgments are made about them and particular responses are made to them. All of these particulars are bound together in an instance representation. The binding may be tight, with everything locked in place, like a snapshot. Or it may be loose, with most of the structure derived at retrieval time (Logan et al., 1996). The main point is that instances represent co-occurrences, and the results support that assumption.

The present experiments complete a long series of category-search experiments that used the same task, items, procedure, and subject population (Boronat & Logan, 1997; Logan & Etherton, 1994; Logan et al., 1996). In all these experiments, subjects saw two words in two locations. In some, their attention was directed to one of the words by a color cue. In others, their attention was divided between the words. Some experiments addressed co-occurrence of the words in the pairs, showing that subjects encoded associations between words when they divided attention between the words but not when they focused on one and ignored the other (Boronat & Logan, 1997; Logan & Etherton, 1994). Other experiments addressed co-occurrence of words and the color cue that directed attention to them, showing that subjects encoded color–word associations but did not always retrieve them in time for them to affect automatic performance (Logan et al., 1996). The present experiments complete the series, addressing co-occurrence of words and locations and showing that subjects encode location–word associations but have trouble retrieving them.

All of the experiments in the series used essentially the same procedure, and that allows us to scale the importance of the different kinds of co-occurrences, in terms of the magnitude of the transfer costs produced by breaking them. Associations between the words in a pair seem more important than associations between words and locations, which in turn seem more important than associations between words and colors. This is an important conclusion because it suggests that all parts of an instance are not represented equally. Instance representations appear to be constellations of loosely connected associations rather than rigid snapshot-like replicas of the stimulus. Moreover, previous experiments suggest that instances may contain associations between stimuli and responses (Logan et al., 1996) and associations between stimuli and interpretations (Logan, 1990) as well as associations between different parts of the stimulus.

It is not clear that the ranking of instance components in category search will generalize to other tasks and other kinds of displays. On the one hand, Lassaline and Logan (1993) found that neither identity nor color was important in a counting task, which is inconsistent with the ranking from category search. On the other hand, Treisman et al. (1992) found that location was more important than color and texture in a conjunction search task, which is consistent with the ranking from category search. Most likely, the ranking of importance of components will vary from task to task, depending on the role that the components play in performing the task. Our results should generalize to related category search tasks, which have been important in the development of the automaticity literature (see, e.g., Schneider, 1985).

Principles or Theories?

The instance theory exists at a number of different levels. At one level, it is a formal theory that makes quantitative predictions about changes in the distribution of reaction times over practice (e.g., Logan, 1992). At another level, it is a collection of principles like "automaticity depends on attention" and "automaticity is a memory phenomenon" that makes predictions about qualitative effects, like transfer costs. The formal theory is much more limited in scope than the collection of principles, but its predictions are more precise and are thus more susceptible to falsification. Depth and breadth trade off.

I think it is time to develop the formal theory further to broaden the scope of its precise predictions. The first step in that development is to combine the instance theory with a theory of attention. Bundesen's (1990) theory of attention is a natural match in many ways (see Logan, 1996), and I plan to explore that combination (see Logan, Taylor, & Etherton, in press).

Readers may debate the utility of developing a precise combined theory. The theory is bound to be wrong. Some would argue that little can be gained from falsifying a specific formal theory, and the field would be better off learning about the operation of principles of attention and memory that transcend specific theories. I believe we can learn a lot from discovering why a specific formal theory is wrong, including something about the operation of general principles. In learning why the theory is wrong, we might learn a little more about what is right. We can try to be deep and broad at the same time.

The advantage of a combined theory is a more precise account of the data. Instance-theory assumptions about memory will constrain the predictions about attention, and the attention-theory assumptions about immediate processing will constrain the predictions about automaticity. Ideally, the constraints would be quantitative. The magnitude of attentional effects would determine the magnitude of automaticity effects, and vice versa. Scaling the magnitudes of predictions is an important step forward from testing qualitative predictions drawn from general principles. For example, a general principle may allow us to predict the direction of a transfer effect given an attentional effect in training, but when that principle is instantiated in a formal theory, the parameter values required to account for the attentional effect may underpredict the transfer effect. The qualitative test (direction of the transfer effect) would suggest that the general principle applies, whereas the quantitative test (magnitude of effects) says it does not. In the present article, Experiments 3–6 suggest that retrieval failure in the form of cue overload was responsible for the null sensitivity to location change in Experiments 1 and 2, but we do not know for sure that the magnitude of the cue-overload effect was sufficient to produce the null sensitivity. A formal memory model might predict more sensitivity than we found in Experiments 1 and 2, and that would falsify the instance theory.

Conclusions

The experiments are consistent with the hypothesis that location information is encoded obligatorily during automatization. Whether or not location information is retrieved at transfer depends on the number of words associated with each location (cue overload), retrieval being less likely when more words appear in fewer locations. These results are consistent with the attention hypothesis (Boronat & Logan, 1997; Logan & Etherton, 1994; Logan et al., 1996) and with the instance theory of automaticity (Logan, 1988, 1990).

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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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