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Context-Dependent Recognition Memory: The ICE Theory

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A solution to the problem of context-dependent recognition memory is presented in terms of the item, associated context, and ensemble (ICE) theory. It is argued that different types of context effects depend on how context information is encoded at both learning and retrieval. Matching associated context in memory and a retrieval cue produces increases in both hit and false alarm rates and may not be accompanied by a change in discrimination. Integrating item and context information in an ensemble and matching ensemble information in memory and a retrieval cue produces context-dependent discrimination. Empirical support for these predictions is presented.

Any theory of memory must provide an answer to the fundamental question of how memory occurs for individual episodes from the past. Under most circumstances we can easily remember specific, individual events when we wish to do so. For example, last night's dinner menu, a performance one attended and enjoyed, or a conversation with a colleague or family member can usually be remembered with little difficulty. The ability to remember past events is so commonplace that we are often surprised and frustrated when it fails. However, the ease with which past episodes are remembered is puzzling if one considers that an individual episode must be retrieved from among the many events stored in memory over a lifetime. Success at episodic retrieval is even more puzzling if one further considers that retrieved episodes are often very similar to many other events stored in memory. How is it that a person can generally remember a particular conversation with his or her spouse from among the many conversations with the same person, on the same or similar topics?

The answer that is often given to this question rests on two ideas that are basic to almost all theories of memory. The first is that an event stored in memory is composed of a range of information that includes both information that was in the focus of attention and information that was present in the processing environment but was peripheral to the focus of attention when encoding into memory took place. This peripheral information is often referred to as context information and may include factors such as details of the physical environment in which learning occurred, information about the emotional or physiological state of the learner, stray thoughts that occurred during learning, and so forth. Taken as a whole, this broad set of information is thought to be sufficient to uniquely specify an event in enough detail to distinguish it from other similar events stored in memory. We will refer to the set of context information that specifies an individual event as *episode-defining context.*

The second idea that provides a foundation for explanations of episodic memory is that the match between information in a retrieval cue and information stored in memory is a critical determinant of success in retrieval. The higher the degree of match, overlap, or similarity between the information contained in a retrieval cue and the information stored in memory, the higher the probability that the information from memory will be successfully retrieved. Thus, the best cue for retrieving a target item from memory is information that is stored in memory along with the target item. Tulving (1983; Tulving & Thomson, 1973) referred to this idea as the *encoding specificity* principle.

Taken together, episode-defining context and encoding specificity provide a straightforward basis for explaining episodic memory. Context information that is automatically stored in memory during learning plays an important role in distinguishing one stored episode from another. Inclusion of this episode-defining context information in a retrieval cue produces a high degree of match with the context information in the episode stored in memory, and this high degree of match increases the probability of retrieving the unique episode. At a simple level of analysis, this general solution to the problem of how episodic memory occurs is common to almost all theories of memory.

A straightforward prediction can be derived from the hypothesis that matching episode-defining context information in memory and a retrieval cue is an important determinant of episodic memory: Testing memory in a context that is different from the learning context should result in lower performance than testing that takes place in the learning context. This prediction has often been supported when memory is tested with a free recall test (see Smith, 1988, for a review, and Fernandez & Glenberg, 1985, for an important

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exception). However, demonstrations of the expected effect of testing in a changed context have been unreliable when memory is tested with a recognition test (Smith, 1988). Although a number of explanations for the variable recognition findings have been proposed over the past two decades (see Smith, 1994, for a review), none have proven wholly satisfactory.

The failure to find a satisfactory explanation for the variable recognition findings is troubling because it raises doubts about the fundamental and widely accepted ideas that context information plays an important role in specifying unique episodes, that matching information in a retrieval cue and memory is an important determinant of successful retrieval, and that the match of episode-defining context in a retrieval cue and memory produces episodic recognition. This, in turn, arouses the suspicion that theories of memory that rely on these principles to explain episodic memory may be flawed. In this article we differentiate between different types of effect that changes in context can have on recognition, demonstrate the conditions in which each type of context effect occurs, and present a theory called ICE (item, associated context, and ensemble) that provides an explanation of why the different types of effect occur.

Context-Dependent Recognition

In accordance with the widely held view that episodic memory is context-dependent, investigators have generally sought evidence that a change in context between learning and test has a negative effect on the ability to discriminate previously learned items (targets) from new items (distractors) in a recognition paradigm (Smith, 1988). We will use the term *context-dependent discrimination* to refer to a change in the ability to discriminate targets from distractors as a result of changes in context information between learning and test. The hallmark of context-dependent discrimination is lower performance in different-context test conditions than in same-context test conditions as measured by the standard measure of discrimination derived from signal detection theory, d'. Previous researchers that have manipulated environmental context and reported context-dependent discrimination include Geiselman and Glenny (1977), Geiselman and Bjork (1980), Smith (1986), and Smith and Vela (1992). Researchers that have reported a failure to produce context-dependent discrimination with changes in environmental context include Fernandez and Glenberg (1985), Godden and Baddeley (1980), Jacoby (1983), Murnane and Phelps (1993, 1994, 1995), and Smith, Glenberg, and Bjork (1978). However, it must be noted that not all studies that have explored context-dependent discrimination have used d' as a dependent measure, and in some cases it is unclear whether the dependent measure reported for a particular study provides a valid measure of discrimination.

Murnane and Phelps (1993, 1994, 1995) showed that changes in context between learning and test can have reliable effects on performance in a recognition task other than a decrease in discrimination. Murnane and Phelps presented a series of studies that demonstrated that under the appropriate circumstances, both hit rate (HR) and false alarm rate (FAR) are higher when recognition testing takes place in the learning context than when it takes place in a new context that was not seen during learning. Discrimination is generally not affected in the conditions identified by Murnane and Phelps because the increase in discriminability caused by increases in HR is offset by the decrease in discriminability caused by increases in FAR. We will use the general term *context-dependent recognition* to refer to any change in recognition performance that is produced by changes in context between learning and test. Thus, both context-dependent discrimination and the same-direction changes in HR and FAR with changes in context reported by Murnane and Phelps qualify as instances of context-dependent recognition as we use the term. If a theory is to offer a complete explanation of context-dependent recognition, it must account for both those cases in which a change in context produces context-dependent discrimination and those cases in which a change in context produces same-direction changes in HR and FAR without producing context-dependent discrimination.

Item, Associated Context, and Ensemble Information

In order to account for both forms of context-dependent recognition, ICE models recognition in terms of three types of information: item, associated context, and ensemble. *Item information* is defined as any information in the processing environment that is necessary or central to the primary cognitive task being performed. *Context information* is defined as any information in the processing environment that is incidental or peripheral to the primary cognitive task being performed. *Ensemble information* is defined as a type of information that is created by combining or integrating item and context information. Note that ensembles are created by the person processing the information at either learning or retrieval. Although constructed from item and context information, ensemble information is thought to be a unique type of information that is different from either item or context information considered alone. To avoid confusion between context information integrated in an ensemble and context information included in either memory or a retrieval cue that is not integrated in an ensemble, we will henceforth refer to the former as *integrated context* and the latter as *associated context.*

The three types of information can be defined by their respective patterns of (mis)match between information in memory and a retrieval cue across the four types of test item that are used in the typical recognition paradigm designed to examine context-dependent discrimination. These patterns are shown in Table 1. As can be seen in the table, item information matches if the test item is a target whether the test context is the learning context or a new context, and associated context information matches if an item is tested in the learning context whether the test item is a target or a distractor. In contrast, ensemble information only produces a match for targets tested in the learning context. This property follows directly from the definition of the ensemble as a unique integration of the learned item and the context in which the item is learned.

Table 1
Patterns of Match for Item, Associated Context, and Ensemble Information

Type of information	Learning context		New context	
	Targets	Distractors	Targets	Distractors
Item	+	−	+	−
Associated context	+	+	−	−
Ensemble	+	−	−	−

Note. + = match; − = mismatch.

Examples of formal mechanisms that can be used to model the creation of an ensemble from the integration of item and context information can be drawn from models in which items are represented as vectors of features (e.g., Hintzman, 1988; Humphreys, Bain, & Pike, 1989; Murdock, 1993; Shiffrin & Steyvers, 1997). Several methods are available for combining a vector that represents item information with a vector that represents context information to produce a vector or a matrix that represents ensemble information. Ensembles can be represented as matrix products of item and context vectors in the matrix model (Humphreys et al., 1989). Another alternative can be found in the TODAM (theory of distributed associative memory) family of models (Murdock, 1993) in which individual items are represented as feature vectors and the association between two items in a studied pair is represented as the convolution of the two item vectors. A straightforward extension of TODAM would involve convolving an item vector with a vector that represents context to produce a vector that represents an ensemble.

A concrete example will help make the distinctions between item, associated context, and ensemble information clear. In the experiments reported in this article, to-be-remembered words are embedded in a picture as illustrated in Figure 1. The words are presented in a location in which it is sensible that words might appear. In Figure 1, the to-be-remembered words are shown on a blackboard in a classroom. Taking the word *DOG* as an example, item information is defined as information about dogs encoded either in memory during learning or in a retrieval cue, which has nothing to do with information about classrooms. Associated context information is defined as encoded information about classrooms that has nothing to do with information about dogs. Ensemble information is defined as integrated information about dogs and classrooms that is encoded either at learning or at retrieval. For example, the participant may own a dog that she recently brought to one of her classes. Presentation of the screen illustrated in Figure 1 may lead her to think of bringing her dog to class, and this self-generated information may then be encoded as ensemble information in the memory representation of the learning event. Another possibility is that the participant may form an ensemble by following a strategy of using the context information to help her remember the to-be-remembered item by constructing a vivid image of a dog teaching a class in full academic regalia.

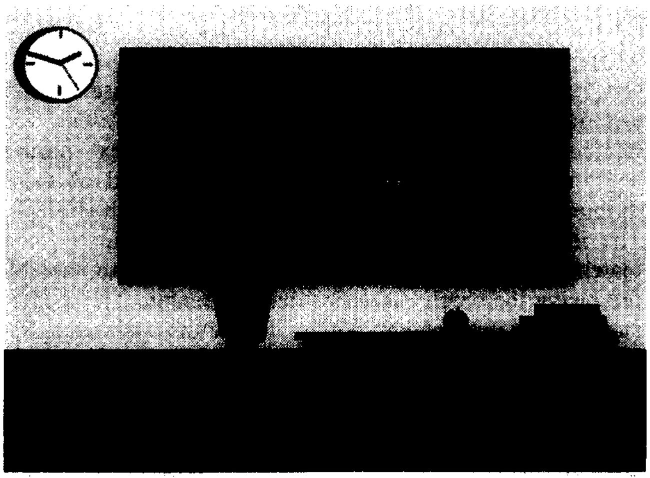

Figure 1. Typical screen presented to participants during the rich visual context conditions of Experiments 1 and 2.

Global Memory Theories

In traditional recognition models (e.g., Anderson & Bower, 1973; Atkinson & Juola, 1974), the recognition process involves accessing the memory representation of the test item in isolation from other information in memory. In contrast, the recognition process in global memory models involves activating sets of memory representations. Individual memory representations are activated based on the match between the information in a retrieval cue and the information in memory. The individual activations are combined to form a global match value that serves as input to a decision process that has typically been modeled using signal detection theory. Examples of global memory theories include Minerva 2 (Hintzman, 1988), TODAM2 (Murdock, 1993), SAM (search of associative memory; Gillund & Shiffrin, 1984), REM (retrieving efficiently from memory; Shiffrin & Steyvers, 1997), and the matrix model (Humphreys et al., 1989; for a detailed, evaluative review of global memory theories, see Clark & Gronlund, 1996).

The activation functions found in all of the theories named above are members of the general class of strictly increasing functions. Moreover, in all of the theories the global match strength is found by adding the activations of the individual memory representations. Let X_j represent the strength of the match between the information in a retrieval cue and the information in the jth item in memory. Then, a general formulation for a global memory system is given by

$$M = \sum_{j=1}^{K} f(X_j),$$

where M represents global activation or global match strength, K is the number of activated memory representations, and f is the activation function.

Global match strength is modeled in ICE in terms of the individual matches between item, associated context, and ensemble information in the cue and in memory. Thus,

$$M = \sum_{j=1}^{K} f(I_j, C, E), \tag{1}$$

where I, C, and E are random variables that may take values from the set of positive real numbers, I represents the strength of the match between item information in the cue and in memory, C represents the strength of the match between associated context information in the cue and in memory, and E represents the strength of the match between ensemble information in the cue and in memory.

Context-Dependent Recognition

Although we assume that match strength varies along a continuous dimension, for purposes of simplicity, assume that item, associated context, and ensemble information in the retrieval cue either matches or mismatches item, associated context, or ensemble information in memory, respectively. Let the subscript H represent a high degree of match strength that is produced when information in memory matches information in the retrieval cue, and let the subscript L represent a low degree of match strength produced when information in the retrieval cue mismatches information in memory. Although intermediate levels of match strength are possible, we will ignore them for the moment. With these assumptions, global match strength is a function of the types of individual match strengths shown in Table 2.

If it is assumed that on average, matched information produces a greater level of activation than mismatched information and that the activation function is strictly increasing with increases in I, C, and E, then the match strengths given in Table 2 have the following inequality relationships:

$$f(I_H, C_H, E_H) > f(I_H, C_L, E_L)\ ?\ f(I_L, C_H, E_L) > f(I_L, C_L, E_L).$$

The relationship between activation quantities when only one factor matches, $f(I_H, C_L, E_L)$ and $f(I_L, C_H, E_L)$, is shown as unknown because it depends on the relative strengths of the item and context matches.

Ordinal predictions based on the above inequality relationships can be derived from ICE by comparing the number and the type of the individual match strengths that contribute to the global sum in different experimental conditions. Predictions regarding how changes in context affect recognition are derived in this article by modeling a list-learning experiment in which participants are given a list of words during a learning phase and are tested with a single-item, old–new recognition test. Learning takes place in several learning contexts, equal numbers of items are presented in each learning context, and each item is presented in one, and only one, context during learning. Items are tested either in one of the learning contexts or in a new context that was not experienced during learning. Different experimental designs will generally necessitate different sets of model equations. We assume that information about the test item is always present in both memory and the retrieval cue; predictions differ depending on whether associated context and ensemble information are also present in the cue and in memory. Predictions are generated for HR, FAR, and d'.

Table 2
Individual Match Strengths in ICE

	Associated context	
Item	Match	Mismatch
Match	$f(I_H, C_H, E_H)$	$f(I_H, C_L, E_L)$
Mismatch	$f(I_L, C_H, E_L)$	$f(I_L, C_L, E_L)$

Note. I = match strength for item information; C = match strength for associated context information; E = match strength for ensemble information; f = strictly increasing activation function; H = high level of match strength; L = low level of match strength.

First, consider the case in which associated context and item information are present in both memory and the retrieval cue but ensemble information is absent from memory, the retrieval cue, or both. This case was modeled by the general context model and detailed discussions can be found in Murnane and Phelps (1994, 1995). Global activations for targets tested in the context in which they were learned and distractors tested in one of the learning contexts (same-context tests) or either type of test item tested in a new context (different-context tests) are given by the following equations:

$$M_{Ts} = f(I_H, C_H) + (N-1)f(I_L, C_H) + (K-N)f(I_L, C_L), \tag{2}$$

$$M_{Td} = f(I_H, C_L) + (K-1)f(I_L, C_L), \tag{3}$$

$$M_{Ds} = Nf(I_L, C_H) + (K-N)f(I_L, C_L), \tag{4}$$

and

$$M_{Dd} = Kf(I_L, C_L), \tag{5}$$

where the subscripts T and D represent targets and distractors, respectively; the subscripts s and d indicate same- and different-context tests, respectively; and N represents the number of items presented in a given context during learning. The sum in Equation 2 is composed of three different combinations of item and context match strength. The item and associated context information in the cue matches the memory representation of the test item, thereby producing the single $f(I_H, C_H)$ match strength. The associated context information in memory and the cue match, but the item information mismatches for the other $(N-1)$ items from the learning list that were learned in the test context, thus producing the $(N-1)f(I_L, C_H)$ match strengths. Finally, the item and associated context information in the cue mismatches everything else in memory, thus producing the $(K-N)f(I_L, C_L)$ match strengths. For distractors tested in one of the learning contexts, as illustrated in Equation 4, there are N cases in which the associated context information in the cue matches the associated context information in the memory representations of the list items, and $(K - N)$ cases in which the information in the cue completely mismatches the activated information in memory. For distractors tested in the new context, as illustrated by Equation 5, both the item and the associated context information in the retrieval cue mismatch everything in the activated set.

There are $(K - N)f(I_L, C_L)$ factors that are common to Equations 2–5. Eliminating these factors from Equations 2 and 3 leaves

$$M^*_{Ts} = f(I_H, C_H) + (N - 1)f(I_L, C_H)$$

and

$$M^*_{Td} = f(I_H, C_L) + (N - 1)f(I_L, C_L)$$

as the factors that contribute to the difference in global activation between same- and different-context tests for targets, where the symbol * is used to indicate that common terms have been eliminated from the global activation equations. The associated context match in same-context tests produces higher levels of global activation than the associated context mismatch in different-context tests because $f(I_H, C_H)$ is greater than $f(I_H, C_L)$ and $f(I_L, C_H)$ is greater than $f(I_L, C_L)$. Because higher levels of global activation indicate an increased probability of an "old" response, HR is predicted to be higher in same-context test conditions than in different-context test conditions.

For distractors, removing the $(K - N)f(I_L, C_L)$ factors shared by Equations 4 and 5 leaves

$$M^*_{Ds} = Nf(I_L, C_H)$$

and

$$M^*_{Dd} = Nf(I_L, C_L).$$

Again, global activation is predicted to be higher for same-context tests than for different-context tests because $f(I_L, C_H)$ is greater than $f(I_L, C_L)$. Thus, FAR is also predicted to be higher in same-context test conditions than in different-context test conditions.

Context effects for d' will tend to be absent when memory and the retrieval cue contain item and associated context information but not ensemble information because global match strength for both targets and distractors is predicted to increase in same-context test conditions. Note, however, that under a limited set of conditions defined by the nature of the activation function and the magnitude of the differences between high and low match strengths, context-dependent discrimination can be produced by matching associated context information. We will return to this issue in the General Discussion.

Next, consider the case in which item and ensemble information are present in both memory and the retrieval cue but associated context information is absent. Global activations for the four cases of interest are given by

$$M_{Ts} = f(I_H, E_H) + (K - 1)f(I_L, E_L), \tag{6}$$

$$M_{Td} = f(I_H, E_L) + (K - 1)f(I_L, E_L), \tag{7}$$

$$M_{Ds} = Kf(I_L, E_L), \tag{8}$$

and

$$M_{Dd} = Kf(I_L, E_L). \tag{9}$$

Removing the $(K - 1)f(I_L, E_L)$ factors shared by Equations 6 and 7 produces

$$M^*_{Ts} = f(I_H, E_H) \tag{10}$$

and

$$M^*_{Td} = f(I_H, E_L). \tag{11}$$

It is readily apparent on examination of Equations 10 and 11 that context effects are predicted for targets because $f(I_H, E_H)$ is greater than $f(I_H, E_L)$. Likewise, it is obvious on examination of Equations 8 and 9 that context effects are predicted to be absent for distractors. The increase in global match strength for targets combined with no change in global match strength for distractors tends to produce an effect for d'. Thus, changes in context will tend to affect discrimination if context is integrated in an ensemble in both memory and the retrieval cue and is not included as associated context in memory, the retrieval cue, or both.

Finally, consider the case in which memory and the retrieval cue contain item, associated context, and ensemble information. The four cases of interest are given by

$$M_{Ts} = f(I_H, C_H, E_H) + (N - 1)f(I_L, C_H, E_L) + (K - N)f(I_L, C_L, E_L), \tag{12}$$

$$M_{Td} = f(I_H, C_L, E_L) + (K - 1)f(I_L, C_L, E_L), \tag{13}$$

$$M_{Ds} = Nf(I_L, C_H, E_L) + (K - N)f(I_L, C_L, E_L), \tag{14}$$

and

$$M_{Dd} = Kf(I_L, C_L, E_L). \tag{15}$$

Removing the $(K - N)f(I_L, C_L, E_L)$ factors that are common to all four equations produces

$$M^*_{Ts} = f(I_H, C_H, E_H) + (N - 1)f(I_L, C_H, E_L), \tag{16}$$

$$M^*_{Td} = f(I_H, C_L, E_L) + (N - 1)f(I_L, C_L, E_L), \tag{17}$$

$$M^*_{Ds} = Nf(I_L, C_H, E_L), \tag{18}$$

and

$$M^*_{Dd} = Nf(I_L, C_L, E_L). \tag{19}$$

Examination of Equations 16–19 shows that matching associated context at learning and test increases context effects for both targets and distractors whereas matching ensemble information at learning and test increases context effects for targets only. Therefore, when the retrieval cue contains item, associated context, and ensemble information, HR and FAR are predicted to increase in same-context test conditions (because of the associated context match), with the increase for HR predicted to be greater than the increase for FAR (because of the ensemble match). If the difference between the increases in global match strength for targets and distractors is of sufficient magnitude, context effects for d' are also predicted.

Predictions from ICE regarding context-dependent recognition are summarized in Table 3. All forms of context-dependent recognition are predicted to be absent if neither the associated context nor the ensemble information in the retrieval cue matches the activated information in memory. If only the associated context information in the retrieval cue matches the associated context information encoded in memory, then HR and FAR are predicted to be higher in same-context test conditions than in different-context test conditions, and a context effect is unlikely for d'. If only the ensemble information in the retrieval cue matches the ensemble information encoded in memory, then HR and d' are predicted to be higher in same-context test conditions than in different-context test conditions and FAR is expected to be the same in same- and different-context test conditions. Finally, if both the associated context information and the ensemble information in the retrieval cue match the associated context and ensemble information in memory, then HR and FAR are predicted to be higher in same-context test conditions than in different-context test conditions, the magnitude of the context effect for HR should be greater than the magnitude of the effect for FAR, and a context effect for d' is possible.

Several previous investigators have suggested that context-dependent discrimination depends on differences in how context information is encoded during learning. Baddeley (1982), Eich (1985), and Bjork and Richardson-Klavehn (1989) drew distinctions similar to our ensemble and associated context and suggested that ensemble encoding during learning produces context-dependent discrimination. Likewise, in the matrix theory of Humphreys et al. (1989), probing memory with a configural cue composed of item and context information, similar in conception to our ensemble, produces context-dependent discrimination. Humphreys et al. (1989) also point out that combining item and context information additively in a retrieval cue, similar in conception to our associated context, produces equivalent changes in HR and FAR and hence no change in context-dependent discrimination in the matrix model. Finally, Dosher and her colleagues (e.g., Dosher, 1991; Dosher, McElree, Hood, & Rosedale, 1989; Dosher & Rosedale, 1989) examined the effects of associated context and ensemble information on semantic priming in recognition and found that ensemble matching increased HRs while associated context matching increased both HR and FAR.

Table 3
Predictions From ICE

Information match		Context effects		
Associated context	Ensemble	HR	FAR	d'
no	no	no	no	no
yes	no	yes	yes	unlikely
no	yes	yes	no	yes
yes	yes	yes	yes	possible

Note. ICE = item, associated context, and ensemble theory; HR = hit rate; FAR = false alarm rate.

Empirical Studies

ICE specifies a global matching recognition system that is capable of producing the full pattern of context-dependent recognition effects. According to the theory, specific predictions depend on patterns of match and mismatch for associated context and ensemble information. ICE, however, is not a theory of how context is encoded at either learning or test. Thus, empirical tests of ICE must be made in conjunction with auxiliary hypotheses about ensemble formation and the encoding of associated context information.

Murnane and Phelps (1993, 1994, 1995) presented a series of studies that examined context-dependent recognition by manipulating the foreground color, background color, and screen location of items at both learning and test. We refer to this type of context information as simple visual context. Context effects for HR and FAR, but not for d', were observed in over 70% of the relevant cases drawn from nine experiments reported by Murnane and Phelps. This is the pattern of results predicted by ICE if item and associated context, but not ensemble information, match at learning and test. Why were ensembles not formed from the type of context information manipulated by Murnane and Phelps? One possibility is based on the finding that more meaningful materials are remembered better (e.g., Baker & Santa, 1977); the probability of ensemble formation may be a function of the amount of meaningful content in the context information. Simple visual context information is low in meaningful content, and for this reason, it may be difficult to elaborate the to-be-remembered item information by integrating it with simple visual context. If this hypothesis is correct, context information that is relatively rich in meaningful content should be more easily integrated into an ensemble through a process of item elaboration.

To test this hypothesis, context was operationally defined as a picture presented on a computer screen such as the picture of a classroom shown in Figure 1. We refer to this type of context information as rich visual context because, in comparison with simple visual context, it is rich in meaningful information. The ready availability of a variety of meaningful information in rich visual contexts provides an opportunity for forming an ensemble. If encoding and retrieval processes take advantage of this opportunity, ensemble information should be present in memory and in the retrieval cue. However, in addition to meaningful information, rich visual contexts also contain a good deal of simple visual information such as colors, screen locations, and so forth. If this simple visual information is encoded as context information that is not included in the ensemble, both memory and the retrieval cue should also contain associated context information. If meaningful context information is integrated with item information in an ensemble and simple visual context information is encoded as associated context, manipulation of rich visual context information should produce context effects for HR and FAR because of the associated context match, the effect for HR should be larger than the effect for FAR because of the ensemble match, and if the difference between the increases in global match strength for targets and distractors is great enough, context effects should also be observed for d' (see Equations 12–15).

Experiment 1

Method

Participants. One hundred sixty volunteers from undergraduate psychology courses received course credit in return for their participation in the experiment.

Design. The learning phase of the experiment consisted of 32 trials of an incidental learning task in which participants judged the relatedness of word pairs on a scale from 1 (*Not very related*) to 5 (*Very related*). An incidental learning task was used to determine whether rich visual context information is integrated with item information in an ensemble in the absence of encoding strategies designed to improve memory performance. Eight learning pairs were presented in each of four learning contexts, and the contexts were randomly intermixed during both learning and test. Word pairs were presented during learning to reduce cross-context encoding of to-be-remembered items. The contexts were pictures of scenes containing a focal object on which it was sensible to display words. These included a television in a living room, a sign on the side of a desert road, a banner trailing from an airplane, a delivery truck parked in front of a building, and a chalkboard in a school classroom. The fifth context did not appear during the learning phase and was used for different-context recognition tests.

Presentation of the instructions for the recognition test provided a natural filler task between the learning and test phases of the experiment. The test phase consisted of 64 single-item, old–new recognition tests. Tests were of single items rather than word pairs to make the task more difficult and eliminate ceiling effects.[1] Targets were 32 single words taken from each of the study pairs, and distractors were 32 new words. Only one word from each study pair was tested, with the constraint that equal numbers of targets were drawn from the first and second members of the study pairs. Half of the targets were tested in their learning context, and half of the distractors were equally divided among the four learning contexts (same-context tests). The remaining targets and distractors were tested in the context not presented during the learning phase (different-context tests). Presentation order of learning and test items was randomized for each participant.

In addition to the basic design described above, instructions to participants were varied in an attempt to influence the degree to which the manipulated context information was encoded in an ensemble during learning and at test. Neutral learning-phase instructions indicated that the aim of the experiment was to gather basic information about how words are understood in a college-aged population. Ensemble instructions emphasized making active use of the picture contexts while making relatedness judgments because the experiment was designed to investigate the effect of the environment in which words appear on how those words are understood. Parallel test-phase instructions either described the nature of the recognition tests or, in addition, told participants to make use of the pictures in which the test items appeared when making their recognition decisions. Learning- and test-phase instructions were completely crossed. Participants receiving ensemble instructions were given a brief reminder message every seventh trial to encourage them to follow the instructions. To summarize, the experimental design was a 2 × 2 × 2 mixed factorial with learning and test instructions (neutral, ensemble) manipulated between subjects and test context (same, different) manipulated within subjects.

Procedure. The experiment, including all instructions and tasks, was presented using IBM-compatible computers equipped with color monitors. Experimental sessions included between 1 and 7 participants who sat at desks in individual booths. Participants read the learning-phase instructions, were given eight practice trials of the relatedness-judgment task, performed the relatedness-judgment task, read the instructions for the recognition test, and performed the recognition test. During the learning phase, word pairs were displayed in black with one word two spaces below the other in the center of a focal object in the scene (e.g., on the television). Each pair was displayed for 5 s followed by a prompt to enter a relatedness judgment. The prompt disappeared upon response or after 3 s. Test items on the recognition test were presented in the center of each focal object until a response was entered or for a maximum of 3 s. Recognition decisions were entered using the *D* and *K* keys. Mapping of keys to response was counterbalanced across participants and instructional conditions. Two seconds of blank screen separated all trials in the experiment.

Materials. Study and test items were drawn from a set of 96 high-frequency nouns (Francis & Kucera, 1982). Stimuli were randomly assigned to conditions for each participant within the constraints described above. All pictures were presented in color.

Results and Discussion

Results are presented in terms of HR, FAR, and d' (see Table 4). Mean d' scores were calculated from individual participant d's (HRs of 1.00 and FARs of 0.00 were adjusted to 0.95 and 0.05, respectively). An alpha level of .05 was adopted for all reported significance tests.

Mixed factors analyses of variance (ANOVAs) were conducted separately for each dependent measure. The factors for these analyses were learning instructions, test instructions, and test context. Test context was the only

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[1] Presentation of word pairs may have resulted in the formation of item–item ensembles during learning. The use of single-item tests precludes the possibility of including a (mis)matching item–item ensemble in the retrieval cue, and thus item–item ensembles in memory, if they are present, should not contribute to global match values. In this article, item–item ensembles are not formally represented in the model equations to simplify the derivation of the predictions and clarify the presentation of the theory. ICE can be easily extended to include other types of ensembles when circumstances warrant.

Table 4
Hit Rates, False Alarm Rates, d's, and Context Effects for Experiment 1

Test instructions	Relatedness judgment instructions					
	Neutral			Use context		
	SC	DC	CE	SC	DC	CE
Neutral						
d'	1.94	1.80	0.14	1.85	1.66	0.19
HR	.83	.75	.08	.83	.71	.12
FAR	.21	.16	.05	.23	.17	.06
Use context						
d'	1.88	1.75	0.13	1.88	1.67	0.21
HR	.81	.75	.06	.85	.75	.10
FAR	.21	.18	.03	.24	.19	.05

Note. SC = same-context tests; DC = different-context tests; CE = context effect; HR = hit rate; FAR = false alarm rate.

statistically significant factor, with same-context tests producing higher HRs, FARs, and *d'*s than different-context tests, $F(1, 156) = 55.79$, $MSE = 0.01$, $p < .0005$; $F(1, 156) = 18.24$, $MSE = 0.01$, $p < .0005$; and $F(1, 156) = 8.97$, $MSE = 0.25$, $p = .003$, respectively. Remaining main effects and interactions were not statistically significant. An additional ANOVA, which included dependent measure (HR, FAR) as a factor, revealed a significant interaction between test context and dependent measure, $F(1, 156) = 8.69$, $MSE = 0.01$, $p = .004$, indicating that test context had a larger effect on HR than on FAR. The main effects in this analysis are not of theoretical interest because they are either collapsed across HRs and FARs or merely showed that HRs were larger than FARs. The remaining interactions failed to reach statistical significance.

The results of Experiment 1 are an important verification of predictions from ICE because they clearly illustrate both context-dependent recognition in the form of same-direction context effects for HR and FAR and context-dependent discrimination in the form of a context effect as measured by *d'*. ICE predicts context-dependent recognition in the form of same-direction changes in HR and FAR as a consequence of encoding associated context information during learning and inclusion of the same associated context information in the retrieval cue. ICE predicts context-dependent discrimination in the form of a context effect as measured by *d'* as a consequence of the integration of the manipulated context information with item information into an ensemble at learning coupled with the inclusion of the same ensemble in the retrieval cue. According to ICE, matching ensemble information at learning and test produces context effects for targets and has no effect on distractors. The clear pattern of context effects for HR being twice the size of context effects for FAR in three of the four conditions of the experiment is consistent with this prediction.

At first glance, the finding that the instructions designed to enhance the integration of rich visual context information in an ensemble had no effect is surprising. There was a clear trend in the data indicating an increase in context-dependent discrimination when ensemble instructions were given during learning, but this trend was not statistically reliable. It may have been the case that the instructions to "use" the rich visual context information when making relatedness judgments were too vague and hence were relatively ineffective. More concrete instructions, such as explicit instructions similar to those used by Eich (1985) to form an image that integrates the words with the picture in which they appear, may have produced a stronger effect. However, the combination of an incidental memory test, the statistically reliable main effect of test context on *d'*, and the lack of an interaction between test context and instructions indicates that rich visual context information tends to be encoded by default in an ensemble during learning when a memory test is not expected.

Experiment 2

The logic of Experiment 1 depends, in part, on the assumption that meaningful context material is likely to be integrated into an ensemble. Observation of context-dependent discrimination in Experiment 1 combined with our prior failures to find context-dependent discrimination in studies that manipulated simple visual context information (Murnane & Phelps, 1993, 1994, 1995) support this assumption. This interpretation of the results of Experiment 1 may be questioned, however, on the grounds that the experiment differed from our prior studies using simple visual context along a number of dimensions other than the type of manipulated context information. For example, a smaller number of items were presented in each learning context in Experiment 1 than in most of our prior studies. Context-dependent discrimination may have been observed in Experiment 1 and not in the experiments using simple visual contexts because context was relatively less overloaded as a retrieval cue for a recall-like process in Experiment 1. In order to eliminate this possible alternative, as well as any others that rest on differences in experimental design between Experiment 1 and prior studies that have manipulated simple visual contexts, type of context (simple or rich) was manipulated within-subject and within-list in Experiment 2.

To the best of our knowledge, Experiment 1 is the only published study that has manipulated rich visual context both within-subject and within-list and has used a new context that was not experienced during learning in different-context test conditions, two factors that Murnane and Phelps (1993) showed are critical for examining associated context encoding. Experiment 2 replicates these basic conditions and, in addition, modifies the design of Experiment 1 by informing participants of the impending memory test before learning takes place. Thus, as regards rich visual context, Experiment 2 partially replicates and extends Experiment 1.

Method

Participants. Fifty-five volunteers from undergraduate psychology courses participated in the experiment in return for course credit.

Materials. Stimuli were drawn from a pool of 432 high-frequency words (Francis & Kucera, 1982). All words were randomly assigned to lists and conditions for each participant. Simple visual context was operationalized as a unique combination of foreground color, background color, and screen location. Rich visual context was operationalized as a unique picture. Three simple visual contexts (light green pairs in the upper-left corner of a magenta screen, yellow pairs in the upper-right corner of a blue screen, and magenta pairs in the lower-left corner of a black screen) and three rich visual contexts (a television in a living room, a sign on the side of a road, and a banner trailing an airplane) were seen during learning. Additional simple (white pairs in the lower-right corner of a green screen) and rich (a delivery truck parked in front of a building) visual contexts were used in different-context test conditions.

Design. The learning phase of the experiment consisted of two lists of to-be-remembered word pairs. Each list contained 72 word pairs, half of which were evenly divided between three simple visual contexts and half of which were evenly divided between three rich visual contexts. Simple and rich learning contexts were randomly intermixed on each list for each participant. Because context was likely to change from trial to trial during learning, word pairs were used to minimize cross-context encoding of the to-be-remembered words.

A single-item recognition test followed each list. Each test list contained 144 single words equally divided between simple and rich visual contexts. Half of the tested words were targets and half were distractors. Targets were randomly selected from each of the 72 studied word pairs with the constraints that only one word was tested from each studied pair and that half of the targets originally appeared as the first member of the studied pair and the other half originally appeared as the second member of the studied pair. Half of the targets were tested in the context in which they were learned; the remaining targets were tested in a new context that was not seen during learning. Targets tested in the different-context test condition were tested in the same type of context (simple or rich) in which they were originally learned. Distractors were equally divided between same- and different-context test conditions. The same-context distractors were equally divided among the six (three simple and three rich) contexts that had appeared during learning. The different-context distractors were equally divided between the new simple and rich contexts. To summarize, the design was a 2 × 2 factorial with test context (same or different) and type of context (simple or rich) manipulated within subjects.

Procedure. The experiment, including all instructions and tasks, was presented on PC computers equipped with color monitors. Sessions included between 1 and 7 participants. After reading the instructions, participants engaged in a short practice list, saw the first learning list, performed an arithmetic distractor task, were reminded of the upcoming memory test, and were tested on the first list. A second list composed of learning, distractor task, and test phases followed immediately. Participants were fully informed of the learning and distractor tasks and the memory test before learning took place. During the learning phase, word pairs were presented for 5 s with 1 s of blank screen separating each pair. During the test phase, individual words were presented for 3 s or until the participant responded. Recognition responses were indicated using the *D* and *K* keys on the keyboard. Mapping of response to key was counterbalanced across subjects.

Results and Discussion

Results are presented in terms of HR, FAR, and *d′* (see Table 5). Mean *d′* scores were calculated from individual participant *d′*s (HRs of 1.00 and FARs of 0.00 were adjusted to 0.95 and 0.05, respectively). An alpha level of .05 was adopted for all reported significance tests. Comparison of Tables 4 and 5 shows that *d′* results from the rich visual context conditions of Experiment 2 were much lower than the *d′* scores from Experiment 1, in which only rich visual context appeared during learning. The intermixture of simple and rich visual contexts on the learning list in Experiment 2 may have led participants to give increased attention to the pictures when they appeared. If this occurred, the result could have been higher levels of associated context encoding and lower levels of item and ensemble encoding than would otherwise take place in rich visual contexts. A shift of resources away from the encoding of item and ensemble information to the encoding of associated context information would decrease discrimination because item and ensemble match increase discrimination whereas associated context match does not. Discrimination in simple visual contexts in Experiment 2 is at roughly the same level as that reported by Murnane and Phelps (1994) for single-item recognition in simple visual contexts, indicating that a shift of encoding resources to associated context may have only occurred for rich visual context information. Because encoding resources may have been differentially allocated to associated context information across the simple and rich visual context conditions of Experiment 2, the data were analyzed using separate single-factor ANOVAs for each type of context.

For simple visual contexts there were statistically reliable context effects for both HR, $F(1, 54) = 4.43$, $MSE = .03$, $p = .04$, and FAR, $F(1, 54) = 4.61$, $MSE = .03$, $p = .036$. Context effects were not statistically reliable for *d′*. These are the predicted results if simple visual context information is encoded as associated context but is not integrated in an ensemble.

For rich visual contexts, there were statistically reliable context effects for HR, $F(1, 54) = 51.69$, $MSE = .38$, $p < .0005$, FAR, $F(1, 54) = 28.64$, $MSE = .16$, $p < .0005$, and *d′*, $F(1, 54) = 4.24$, $MSE = .39$, $p = .044$. These are the expected results if rich visual context information is encoded as associated context and is also integrated into an ensemble at both learning and test.

All of the predictions derived from ICE in combination with the hypothesis that ensembles are more likely to be formed when context is rich in meaning regarding HR, FAR, and *d′* were confirmed in Experiment 2. Context-dependent recognition in the form of same-direction changes in HR and

Table 5
Hit Rates, False Alarm Rates, d′s, and Context Effects for Experiment 2

Dependent measures	Type of context					
	Simple visual context			Rich visual context		
	SC	DC	CE	SC	DC	CE
HR	.71	.68	.03	.72	.60	.12
FAR	.34	.31	.03	.33	.26	.07
d′	1.08	1.06	.02	1.12	1.00	.12

Note. SC = same-context tests; DC = different-context tests; CE = context effect; HR = hit rate; FAR = false alarm rate.

FAR were observed in simple visual contexts replicating the prior findings of Murnane and Phelps (1993, 1994, 1995). Context-dependent recognition in the forms of both same-direction changes in HR and FAR and context-dependent discrimination were observed in rich visual contexts replicating the results of Experiment 1. The findings of same-direction changes in HR and FAR for both simple and rich visual contexts indicate that both types of context information are encoded as associated context at learning and at retrieval. The finding of context-dependent discrimination for rich visual contexts but not for simple visual contexts indicates that rich, but not simple, visual context information is integrated in an ensemble at learning and at retrieval. The pattern of context-dependent discrimination findings also supports the hypothesis that the likelihood of ensemble formation is related to the meaningfulness of the context information.

General Discussion

Changes in environmental context between learning and test can have complex effects on recognition memory performance. Context-dependent recognition can take the form of context-dependent discrimination, in which changing the learning context produces a decline in the ability to discriminate targets from distractors, or it can take the form of a decline in both HR and FAR with no effect on discrimination. We have presented an explanation for this pattern of findings derived from a theory named ICE. ICE explains both forms of context-dependent recognition by combining the analysis of same-direction changes in HR and FAR found in the general context model (Murnane & Phelps, 1994) with the idea that item and context information can be integrated to form a different type of information called an ensemble (see Baddeley, 1982; Bjork and Richardson-Klavehn, 1989; Dosher, 1991; Eich, 1985; Humphreys et al., 1989, for similar ideas). Context-dependent discrimination occurs when ensemble information in a retrieval cue matches ensemble information in memory. Same-direction changes in HR and FAR occur when matching context information that is not integrated in an ensemble is included in both memory and a retrieval cue. One and the same memory representation, and one and the same retrieval cue, may contain one, both, or neither type of context encoding. The effects of changes in context on recognition performance depend on how the types of context encoding that are present in memory match with the types of context encoding in the retrieval cue. Dosher and her colleagues (e.g., Dosher, 1991; Dosher et al., 1989; Dosher & Rosedale, 1989) have proposed a similar theoretical mechanism to account for semantic priming effects in recognition that mirror the context effects discussed here.

Ensembles and Context-Dependent Discrimination

Are there conditions under which matching associated context information can produce context-dependent discrimination as measured by d'? Consider the typical experiment in which memory is tested in the learning context. Subtracting Equation 3 from Equation 2 gives an estimate of discriminability for this case:

$$M_T - M_D = f(I_H, C_H) - f(I_L, C_H)$$

Examination of this equation shows that matched associated context, C_H, has offsetting effects on discrimination. When memory is tested with a target, discrimination increases as $f(I_H, C_H)$ increases. However, when memory is tested with a distractor, discrimination decreases as $f(I_L, C_H)$ increases. Matching associated context information can produce context-dependent discrimination if there are circumstances in which strengthening the associated context match results in an enhancement of discrimination for targets that is sufficiently greater than the concomitant decrease in discrimination for distractors.

Figure 2 shows idealized functions that depict how the activation of an individual memory representation increases as the strength of the associated context match increases.

Linear functions are shown but the important relationships depicted by the figure hold for any strictly increasing functions. The upper curve in each panel illustrates the case in which item match strength is high (i.e., the test item is a target), and the bottom curve in each panel shows the case in which item match strength is low (i.e., the test item is a distractor). The right panel of Figure 2 shows a pair of curves that diverge as associated context strength increases; the left panel shows a pair of parallel curves (see Murnane & Phelps, 1995, for a discussion of convergent curves). The activation function, f, determines whether the curves are parallel or divergent. Parallel curves are produced by an activation function in which the effect of changes in associated context match strength is independent of the level of item match strength. For example, simple addition (i.e., $f(I, C) = I + C$) produces parallel activation curves. Divergent curves are produced by activation functions in which the effect of changes in associated context match strength are dependent on the level of item match strength. TODAM (Murdock, 1993) and the matrix model (Humphreys et al., 1989) can produce either divergent or parallel curves with

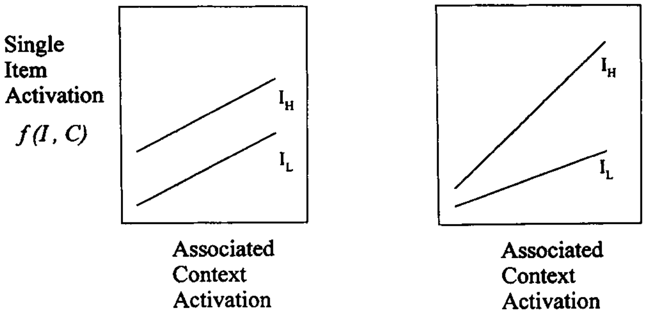

Figure 2. Activation of single items as associated context strength increases. I = strength of the match between item information in the cue and in memory; C = the strength of the match between associated context information in cue and in memory; f = the activation function; H = a high degree of match strength; L = a low degree of match strength.

appropriate representational assumptions, whereas SAM (Gillund & Shiffrin, 1984) and Minerva 2 (Hintzman, 1988) produce divergent curves.

If the activation function produces parallel activation curves, increases in discrimination caused by matched associated context information when memory is tested with a target are exactly offset by decreases in discrimination caused by matched associated context information when memory is tested with a distractor. However, if the activation function produces divergent activation curves, increases in the strength of the associated context match have a relatively greater effect when item match strength is high than when item match strength is low. In other words, for divergent activation functions, matching associated context information at learning and test produces an increase in activation for both targets and distractors, with the increase for targets being greater than the increase for distractors. Thus, models that use a divergent activation function have the potential to produce context-dependent discrimination without the addition of an ensemble. However, because increases in associated context match strength produce increases in HR and FAR, context-dependent discrimination will only be observed if the segments of the curves that are bracketed by high and low context match strengths are sharply divergent.

Could the levels of context-dependent discrimination observed for rich visual context in Experiments 1 and 2 have resulted from a situation in which ensemble information was absent, the activation curves for high and low item match strengths diverged, and the high and low associated context match values bracketed sharply divergent segments of the curves? Comparison of the results when simple and rich visual contexts are manipulated can help answer this question. If the context-dependent discrimination observed for rich visual contexts was caused by (mis)matched associated context information, the magnitude of the context effects for both HR and FAR should be greater for rich visual contexts than for simple visual contexts. The results of Experiment 2 are consistent with the hypothesis that the context-dependent discrimination observed in this experiment was caused by matching associated context and not ensemble information. However, there is little support for this hypothesis when all of the available data are taken into account. Combining the data reported in this article with the data previously reported by Murnane and Phelps (1993, 1994, 1995) shows that the magnitude of the context effect for targets is larger for rich (.098) than for simple (.072) visual contexts but the FAR context effects are almost identical for rich (.053) and simple (.044) visual contexts (difference equals .009). This is the pattern predicted by ICE if context-dependent discrimination in rich visual contexts is caused by matching ensemble information.

Broader Implications

How does the analysis of context-dependent recognition provided by ICE account for the variable context effects found in recognition studies in prior research? Before addressing this question, it must be noted that the wide variety of experimental designs, dependent measures, types of context information manipulated, and methods used to manipulate operationally defined context used in prior studies make it impossible to draw simple conclusions about groups of individual studies.

In general, ICE explains prior failures to show context-dependent discrimination as cases in which the operationally defined and manipulated context information was not integrated in an ensemble in memory, in the retrieval cue, or both. This simple explanation highlights the important idea that whether a type of information fulfills the episode-defining function of context information that is specified by many memory theories depends on how the information is used by the participant. The fact that a particular type of information is highly salient to the investigator and is, therefore, operationally defined as context information for the purposes of a particular experiment does not mean that the participant will integrate that information in an ensemble with item information at both learning and test. Put another way, careful manipulation of a particular type of information does not guarantee that the information will fulfill the theoretical role of context information mandated by theory.

Explaining the absence of context-dependent discrimination in prior research as the result of a failure to integrate the experimentally manipulated context in an ensemble draws attention to an important caveat that should be noted. ICE provides a formal account of several different forms of context-dependent recognition that depend on the (mis)match of item, associated context, and ensemble information in memory and a retrieval cue. This means that ICE can be misused to provide post hoc explanations of several different patterns of data. It is a strength of ICE that the patterns of context-dependent recognition that it predicts are observed in the data. However, the tests of ICE presented in this article depend on accepting the auxiliary hypothesis that the semantic richness of the manipulated context information is an important factor in determining ensemble formation. The results of Experiments 1 and 2 are consistent with, but do not provide a rigorous test of, this auxiliary hypothesis. It is important to realize that at this point, ICE is a theory of retrieval processes in recognition. It is not a theory of ensemble formation. A well-formulated, fully tested, and independently verified theory of ensemble formation would be of great value in laying the groundwork for a powerful test of ICE. The ability of ICE to predict the observed patterns of context-dependent recognition highlights the importance of developing a theory of ensemble formation.

Keeping the foregoing caveat in mind, can the analyses based on simple and rich visual contexts presented here be extended to other types of context information? Simple and rich visual contexts were chosen because they are easy to manipulate and because they differ in the degree to which they are meaningful; there is nothing in ICE that limits its application to these two types of context information. Thus, in principle, the important theoretical conclusions that associated context matching produces increases in hit and false alarm rates and that ensemble matching produces context-dependent discrimination should apply to any type of context information. However, it must be kept in mind that the differences between item and context information on the one hand and between associated context and ensemble encoding on the other are functional differences. The same unit of information may serve as item information in one task and context information in another. Likewise, context information may be encoded as associated context or integrated into an ensemble depending on the type of context information, the type of item information, task demands, or differences in strategies used to accomplish the task. Empirical studies are needed to determine how different types of context information tend to be encoded in different circumstances.

There may also be systematic individual differences in context encoding. For example, clinical populations may differ in the way context information tends to be encoded. One possibility is that depressed patients may have a greater tendency than nondepressed individuals to integrate information associated with their emotional state with information about ongoing events. If so, stored ensembles that incorporate information regarding a depressed emotional state may lead to a greater propensity to "recognize" future events as depressing.

A second example can be found in gerontological studies of memory. It has been well established that older adults do not perform as well as younger adults on many standard episodic memory tasks (for a review, see Craik & Jennings, 1992). This difference might, in part, be caused by differences in context encoding between the two groups. However, as has been the case with examinations of the effects of context information on recognition memory among young adults, empirical evidence has been ambiguous. Some investigators (e.g., Naveh-Benjamin & Craik, 1995) have found no differences in context effects between the young and the elderly, whereas others (e.g., Park, Smith, Morrell, Puglisi, & Dudley, 1990) have found impairments in context processing among elderly as compared with younger adults. Recently, Bayen and Phelps (1997) have reported age-related differences in the encoding of ensemble information accompanied by no age-related differences in the encoding of associated context information. They suggested that the apparent contradictions in the literature may be resolved in terms of systematic differences between the young and the elderly in how context information is typically encoded.

Conclusion

In this article we have examined context-dependent recognition memory with the aid of a theory termed ICE. The theory predicts a variety of effects that depend on how context information is encoded at learning and at retrieval. Context-dependent discrimination results from matching ensemble information in memory and a retrieval cue; context-dependent recognition in the form of same-direction changes in HR and FAR results from matching associated context information in memory and a retrieval cue. Empirical evidence was presented that confirms both of these hypotheses. We believe ICE provides a coherent, empirically verified, theoretical account of the different ways in which context information can affect recognition memory.

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