

Visual cognition in amnesic H.M.: Selective deficits on the What's-Wrong-Here and Hidden-Figure tasks

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Two experiments compared the visual cognition performance of amnesic H.M. and memory-normal controls matched for age, background, intelligence, and education. In Experiment 1 H.M. exhibited deficits relative to the controls in detecting “erroneous objects” in complex visual scenes—for example, a bird flying inside a fishbowl. In Experiment 2 H.M. exhibited deficits relative to the controls in standard Hidden-Figure tasks when detecting unfamiliar targets but not when detecting familiar targets—for example, circles, squares, and right-angle triangles. H.M.’s visual cognition deficits were not due to his well-known problems in explicit learning and recall, inability to comprehend or remember the instructions, general slowness, motoric difficulties, low motivation, low IQ relative to the controls, or working-memory limitations. Parallels between H.M.’s selective deficits in visual cognition, language, and memory are discussed. These parallels contradict the standard “systems theory” account of H.M.’s condition but comport with the hypothesis that H.M. has difficulty representing unfamiliar but not familiar information in visual cognition, language, and memory. Implications of our results are discussed for binding theory and the ongoing debate over what counts as “memory” versus “not-memory.”

Keywords: Visual cognition; Amnesia; Patient H.M.; Error detection; Hidden figures.

Suffering from life-threatening epilepsy at age 26, H.M. underwent a unique and circumscribed form of neurosurgery. The surgeon inserted thin metal tubes above the eyes and, via suction, removed bilateral parts of H.M.’s hippocampus and directly linked medial temporal lobe (MTL) structures. This operation greatly reduced the magnitude and frequency of H.M.’s epileptic episodes and left undamaged all neocortex with known links to visual cognition.

However, H.M.’s lesion caused episodic memory impairments that were both unexpected and severe (see Scoville & Milner, 1957). Because of these impairments, H.M. has become “a touchstone for research on amnesia and memory systems” (Manns, 2004, p. 411). The initial assumption was that H.M. exhibits a pure memory deficit, reflecting

damage to memory-encoding systems but not to other cognitive systems. All current textbooks that discuss H.M. echo this assumption, which has greatly impacted psychological theories since 1968 (see, e.g., MacKay, Burke, & Stewart, 1998a; MacKay, James, Taylor, & Marian, 2007).

However, subsequent research has shown that H.M. has *selective* memory problems, with memory deficits for some types of information and sparing for other types: H.M.’s MTL damage impaired recall of unfamiliar information that he encountered for the first time after his operation, but spared recall of massively repeated information and familiar information encountered frequently before and after his operation. For example, H.M. exhibits memory impairments in

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explicit tests of declarative, episodic, and semantic memory involving novel or never previously encountered information—for example, the definition for an unfamiliar or never previously encountered word (semantic memory) or the fact that a particular word appeared in a particular list (episodic memory). H.M. also exhibits deficits in implicit memory tests involving unfamiliar words or “pseudowords” (Gabrieli, Cohen, & Corkin, 1988). However, H.M. exhibits spared explicit memory in tasks involving familiar information—for example, the definition for familiar words encountered frequently before and after his operation—or massively repeated information—for example, extensively repeated semantic information encountered for the first time after his operation. H.M. also exhibits sparing in implicit memory tests involving preoperatively familiar information—for example, repetition priming for familiar words—or massively repeated information—for example, eyeblink conditioning, mirror tracing, and motor skills tasks (see Gabrieli et al., 1988; Keane, Gabrieli, & Corkin, 1987; Keane, Gabrieli, Mapstone, & Johnson, 1995; MacKay et al., 1998a; O’Kane, Kensinger, & Corkin, 2004; Spiers, Maguire, & Burgess, 2001).

Subsequent research also showed that H.M.’s selective pattern of deficits and sparing was not restricted to memory: H.M. exhibited selective deficits in language comprehension, language production, and reading that precisely mirrored his selective memory deficits (MacKay et al., 1998a; MacKay & James, 2001, 2002; MacKay et al., 2007; and MacKay, Stewart, & Burke, 1998b; see also Corkin, 1984; Lackner, 1974). H.M.’s language-related deficits were not due to his memory problems, to educational deficiencies, or to low motivation or inability to follow the instructions and, together with his selective memory deficits, provided the basis for the following empirical generalization applicable to all aspects of H.M.’s behavior (summarized from MacKay et al., 2007; see also MacKay, James, & Hadley, 2008a):

Empirical Generalization H.M.: H.M. exhibits impaired processing of unfamiliar or never-previously encountered information, and impaired processing of familiar information in unfamiliar or never-previously encountered contexts, but spared processing of massively repeated information and familiar information in familiar contexts encountered frequently before and after his lesion.

Current support for empirical generalization H.M.

Language-related support for empirical generalization H.M. involves language comprehension,

language production, and reading sentences aloud. In language comprehension, H.M. readily understands the multiple meanings of familiar lexically ambiguous words and phrases presented in isolation but he exhibits large deficits in comprehending the same words in unfamiliar sentences. H.M. also exhibits deficits in comprehending metaphors in unfamiliar sentences and in determining whether unfamiliar sentences are ungrammatical or ambiguous, or contain a grammatical error (see MacKay et al., 2007, Experiments 1–6).

In language production, H.M. likewise exhibits deficits when producing unfamiliar but not familiar information. For example, H.M. exhibits deficits when producing unfamiliar phrases in sentences but not when producing familiar phrases or clichés (see MacKay et al., 1998a). Similarly, on the constrained picture description subtest of the Test of Language Competence (Wiig & Secord, 1988), H.M. exhibits deficits when describing unfamiliar situations but not when describing commonly encountered situations via clichés familiar since childhood (MacKay et al., 2007).

In reading, H.M. likewise exhibits deficits when reading aloud unfamiliar but not familiar aspects of sentences. H.M. produces abnormal pauses when reading unfamiliar phrases in sentences and at major syntactic boundaries unmarked by commas. However, H.M. produces normal pauses when reading familiar phrases and at major syntactic boundaries marked by commas, a signal to pause that children learn during grade school (see MacKay & James, 2001).

The present study

The present study reports two figure detection experiments designed to determine whether empirical generalization H.M. applies to visual cognition. Participants were H.M. and the carefully matched memory-normal controls with background characteristics summarized in Table 1. The task in Experiment 1 was to detect visual objects that are “erroneous” or appear in inappropriate or impossible contexts in complex scenes. Figure 1a illustrates this “What’s-Wrong-Here” task for an erroneous object abstracted from a complex picture of a school classroom containing many other erroneous and nonerroneous objects and ongoing activities.

Experiment 2 examined H.M.’s ability to detect familiar versus unfamiliar visual targets in a modified version of the Hidden-Figures Test (Gottschaltdt, 1929; Thurstone, 1949). This experiment followed up on the only published data on

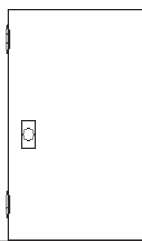
TABLE 1
Characteristics of participants in Experiments 1 and 2

Participants	Age (years)	Highest educational degree	IQ		
			Verbal	Performance	Mean
H.M.	72	High school	107	117	112.00
Control 1	74	High school	114	128	121.00
Control 2	74	High school	110	113	111.50
Control 3	74	High school	115	104	109.50
Control 4	70	High school	107	118	112.50
Control 5	65	High school	115	114	114.50
Control 6	66	High school	111	123	117.00
Mean for Exp. 1	73.00 (2.00)	High school	111.50 (3.70)	115.75 (10.01)	113.63 (5.07)
Mean for Exp. 2	68.75 (4.11)	High school	112.00 (3.83)	114.75 (8.06)	113.38 (3.17)

Note. Experiment 1: Controls 1–4; Experiment 2: Controls 3–6. Standard deviations in parentheses.



A



B

Figure 1. Erroneous objects created to illustrate typical What's-Wrong-Here errors in Experiment 1: (A) a bird in flight in a fishbowl filled with water; (B) a nonfunctional door.

H.M.'s visual cognition: a parenthetical note in Milner, Corkin, and Teuber (1968) that H.M. exhibited an overall deficit on the Gottschaldt–Thurstone test. However, Milner et al. assumed that H.M.'s hidden-figures deficit was solely attributable to his memory problems and not to impaired visual cognition per se, and researchers since then have likewise assumed that H.M.'s visual

cognition is entirely intact (see, e.g., Cohen & Eichenbaum, 1993, pp. 49–219; Schachter, 1990; and Squire, 1987, pp. 152–169). This no-deficit assumption represented the null hypothesis in the present experiments: Failure to reject this null hypothesis would indicate that visual cognition represents an exception to empirical generalization H.M.

EXPERIMENT 1: THE WHAT'S-WRONG-HERE TASK

The What's-Wrong-Here task is a modified version of a children's game that appears in a book series entitled *What's Wrong Here?* (Tallarico, 1991a, 1991b). The task involves several simple steps: Participants inspect a picture of an organized scene containing 11–20 erroneous objects, find an object in the scene that is in error, and circle it. They then briefly explain why the object is in error, a procedure designed to detect guessing and miscomprehension or misrecall of the instructions. Participants next repeat these steps to find and circle as many erroneous objects as possible within a generous time limit.

Figure 1b shows a typical erroneous object abstracted from the same What's-Wrong-Here picture as that in Figure 1a. Figure 1b clearly depicts a nonfunctional or "erroneous" door because its hinges appear on the same side as its door knob. Participants typically explain why this door is erroneous via a simple sentence such as, "The door is impossible to open."

Four ordered processes underlie the successful detection of erroneous objects such as the dysfunctional door in Figure 1b: internal representation, implicit retrieval, comparison, and inference processes.

Step 1: Internal representation

Participants must first construct an accurate internal representation of the erroneous object, here a door with a doorknob on the same side as its hinges. Accurate construction of this internal representation is essential because participants almost certainly have no prior experience with dysfunctional doors and lack a preformed internal representation of such an object in long-term visual memory. This internal representation step underpins future recognition of any object encountered for the first time and entails visual cognition *par excellence* (see Minsky, 2006, pp. 149–159).

Forming an internal representation for an object represents a form of implicit learning (that can be either short term or long term). Importantly, however, detecting erroneous objects involves explicit learning of neither visual information nor episodic/semantic information (areas in which H.M. exhibits well-known deficits): Participants in the What's-Wrong-Here task are not explicitly asked to learn and remember the erroneous objects (which remain in continuous view on each trial).

Step 2: Implicit retrieval

The internal representation for a normal or “canonical” door and how it opens must next be retrieved from long-term visual memory. This memory retrieval step underlies recognition of all familiar objects and likewise entails visual cognition *par excellence*.

However, it is important to note that this retrieval step is implicit rather than explicit. Participants in the What's-Wrong-Here task are not explicitly asked to recollect a canonical door or prior experiences with a canonical door. Note also that adults formed their internal representation for familiar objects such as doors during childhood and have retrieved that internal representation many times in their everyday lives since then.

Step 3: Comparison processes

In Step 3, the frequently used internal representation for the canonical door must be compared with the newly formed internal representation for the dysfunctional door. This step almost certainly involves mechanisms specific to visual cognition *per se*, but is probably unproblematic for H.M. because H.M. has exhibited impaired comparison processes in no prior study involving spatial or any other type of information.

Step 4: Inference and decision

Based on the differences computed in Step 3 between the canonical and dysfunctional door, participants must infer/decide that the dysfunctional door is an erroneous object in its pictured context (a school classroom). This inference-and-decision step may or may not involve mechanisms specific to visual cognition *per se* but is probably unproblematic for H.M. because H.M. has exhibited impaired inference-and-decision processes in no prior study involving spatial or any other type of information.

In summary, processes underlying the detection of erroneous objects seem well suited for testing whether H.M. exhibits deficits in visual cognition that are independent of his well-known deficits in explicit encoding and recall of unfamiliar (episodic and semantic) information. First, the What's-Wrong-Here task requires neither explicit learning nor explicit recall of unfamiliar or newly encountered information: memory domains in which H.M. exhibits well-established deficits. Second, the What's-Wrong-Here task involves implicit retrieval of familiar information (canonical visual objects) learned prior to H.M.'s age 26 lesion, a memory domain in which H.M. does not exhibit deficits (see e.g., Gabrieli et al., 1988).

Method

Participants

Participants were H.M. and the memory-normal controls 1–4 in Table 1. H.M. was tested in 1998 at age 72 when his mean IQ on the verbal and performance subtests of his most recent Wechsler–Bellevue I (W-B I) test was 112 (see Kensinger, Ullman, & Corkin, 2001, for reasons why the W-B I is more appropriate than other, more recently developed IQ tests for testing H.M.). H.M.'s native language was English, his background involved unskilled and semiskilled labor, and his highest educational degree was the high-school diploma.

Table 1 shows the corresponding background characteristics for the controls. We selected the controls from more than 750 older adults in the participant pools of the University of California, Los Angeles (UCLA) Cognition and Aging Laboratory and the Claremont Project on Memory and Aging to match H.M. as closely as possible for native language, background, highest educational degree, mean age at time of test, and mean IQ score on the Verbal and Performance subtests of the W-B I. The controls were engaged in unskilled or semiskilled labor, reported an absence of neurological problems,

spoke English as children, and participated for \$10/hr. Mean age of the controls at test was 73.00 ($SD = 2.00$), and their IQ averaged across the verbal and performance subtests of the W-B I was 113.63 ($SD = 5.07$).

Materials

The materials were three 11×17 " drawings photocopied in color from Tallarico (1991a, 1991b). One was a practice picture, and two were experimental pictures. The practice picture depicted schoolchildren in the lunchroom of a crowded cafeteria. The first experimental picture depicted children exploring the front yard of a "haunted house," and the second depicted children working on various projects in a school classroom. The practice picture contained 11 errors (as indicated elsewhere in Tallarico), and the experimental pictures together contained 33 errors—for example, a telephone receiver replacing a door handle, and an upside-down pot of flowers either on or floating above a desk (see Figures 1a and 1b for other examples). Based on H.M.'s performance on the Boston Naming Test (BNT) at age 72 (see Kensinger et al., 2001), H.M. almost certainly would have been familiar with and capable of naming all of the visual objects in the What's-Wrong-Here pictures when presented in canonical form in isolation. Also familiar to H.M. and the controls was the type of scene (e.g., a school classroom), but not the specific arrangements of objects within the scenes.

Procedure

A summary of the instructions appeared on a card that was prominently displayed throughout the experiment, and the experimenter repeated the instructions verbally: "Carefully examine each picture for errors, and as soon as you find one, circle it on the page with the marker provided. Then briefly explain why the aspect you circled is in error, and then move on to the next error." The experimenter presented the pictures one at a time in the order practice, "haunted house," "school classroom." Sessions were tape recorded to enable subsequent transcription of how participants "explained" the erroneous objects that they circled.

Trials for experimental pictures ended after participants indicated that they could find no more errors or after five minutes, whichever came first. Procedures differed slightly for the unscored practice picture: To ensure experience with the full range of errors to be circled, the practice trial had no time limit, and when participants indicated that they could find no more erroneous objects in the practice picture, the experimenter pointed to the

remaining erroneous objects and explained why they were in error.

Results

Analyses in Experiments 1 and 2 followed two standard conventions: Deficits labeled as reliable involved differences in performance between H.M. and the controls of 2.00 standard deviations or more, and the ceiling descriptor for deficits that were indefinitely large (as can occur when a control group outperforms H.M. with $SD = 0$) was 6.00 standard deviations.

Overall detection of erroneous objects

No participant correctly circled all 33 erroneous objects in the experimental pictures. The mean number of correct responses was 23.00 (70%) for the controls ($SD = 2.94$) versus 16 (48%) for H.M., a difference of 2.38 standard deviations. H.M. therefore exhibited a reliable deficit relative to carefully matched controls in detecting erroneous objects in the What's-Wrong-Here task.

Uncorrected object identification errors

Uncorrected object identification errors were scored when participants applied an incorrect label to an object without self-correction. For example, H.M. called a trash can (partially occluded in the class room picture) "a window" without correction, and he called a rabbit (in the haunted house picture) "a dog" without correction. Overall, H.M. produced 3 uncorrected object identification errors versus a mean of 0.00 for the control participants ($SD = 0.00$), a reliable difference in excess of 6.00 standard deviations. No indications of word-finding difficulties—for example, markers such as "um" and "er"—accompanied H.M.'s uncorrected object identification errors.

Subsidiary results

Verbal explanations of circled objects. H.M. gave no verbal explanation for 3 erroneous objects that he circled, versus a mean of 5.50 unexplained responses for the controls ($SD = 4.43$), a nonreliable difference of 0.56 standard deviations. Moreover, verbally explained erroneous objects were as easy to identify from H.M.'s explanations as from those of the controls. Three judges naïve to speaker identity compared each transcribed explanation with the circled objects in the corresponding experimental picture and labeled an explanation indeterminate if they were unsure what circled object it referred to. Explanations labeled indeterminate by

two or more judges (e.g., “That must be wrong”) were then coded as indeterminate in the final transcript. Under this definition, H.M. produced only 1 indeterminate explanation, whereas controls produced a mean of 4.00 indeterminate explanations ($SD = 3.37$), a nonreliable difference of 0.89 standard deviations.

Words per erroneous object described. Word counts indicated that H.M. produced more words in describing detected errors than did the controls. H.M.’s descriptions contained 8.54 words per erroneous object circled, versus a mean of 5.54 words for the controls ($SD = 1.19$), a reliable difference of 2.52 standard deviations.

Discussion

Two basic findings in Experiment 1 require explanation: H.M.’s overall deficit on the What’s-Wrong-Here task; and the fact that H.M. but not the controls produced uncorrected object identification errors. We first address some implausible hypotheses for explaining these findings. We then relate the present findings to empirical generalization H.M., including H.M.’s language-related deficits. Finally, we address a major hypothesis (the internal representation hypothesis) and two minor hypotheses (a comparison-deficit hypothesis and an inference-deficit hypothesis) for explaining the present findings and guiding subsequent research.

H.M.’s overall deficit in detecting erroneous objects

H.M. exhibited a reliable deficit of 2.38 standard deviations relative to carefully matched controls in detecting erroneous objects in What’s-Wrong-Here pictures. This overall deficit was not due to misrecall of the instructions: H.M. forgot the instruction to verbally explain only 3 circled objects, versus a mean of 5.50 for the controls.

Nor was H.M.’s overall deficit due to miscomprehension of the instructions: In general, H.M. followed the instructions at least as well as the controls—for example, producing only 1 indeterminate explanation for why he circled an object, versus a mean of 4.00 indeterminate explanations for the controls.

Nor was H.M.’s overall deficit due to lack of motivation to succeed on the What’s-Wrong-Here task: With number of words per description taken as an indication of motivation to succeed, H.M. was at least as motivated to succeed as the controls because he produced reliably more words than the controls per erroneous object described.

Nor was H.M.’s overall deficit on the What’s-Wrong-Here task due to poor visual acuity. During the same month as the present study, H.M. was able to accurately identify visual forms that were much smaller than the What’s-Wrong-Here objects (i.e., isolated letters of the alphabet presented in random order; see MacKay & James, 2001, 2002). Also arguing against perceptual difficulties, normal individuals typically indicate perceptual difficulty via spontaneous comments such as, “That looks like a rabbit but it’s hard to make out.” However, neither H.M. nor the controls produced such comments, even when the experimenter pointed out erroneous objects that they failed to circle in the practice picture.

H.M.’s uncorrected object identification errors

H.M.’s overall deficit on the What’s-Wrong-Here task might reflect general slowness, a working-memory deficit, or motoric difficulties in circling the erroneous objects. Versions of these hypotheses might also explain uncorrected errors of omission. However, these hypotheses cannot readily explain uncorrected errors of commission—for example, object identification errors such as calling a trash can “a window” or calling a rabbit “a dog.” Nor can general slowness, a working-memory deficit, or clumsiness in circling erroneous objects explain why someone would fail to correct or indicate confusion regarding such object identification errors.

H.M.’s uncorrected object identification errors were not unintended speech errors or slips of the tongue, involving, for example, substitution of the word “rabbit” for “dog.” Normal individuals usually correct their unintended speech errors (see e.g., Levelt, 1984), whereas H.M. corrected none of his object identification errors.

Nor were H.M.’s uncorrected object identification errors due to temporary inability to retrieve the appropriate name for an object—for example, “rabbit.” First, normal individuals usually indicate word retrieval difficulties via markers such as “um,” “uh,” and “er” (see e.g., Erard, 2007, pp. 78–110), but no such markers accompanied H.M.’s object identification errors. Second, H.M.’s 1999 performance on the Boston Naming Test indicates that he is able to retrieve high-frequency words such as *rabbit* without deficit (see Kensinger et al., 2001). Nonetheless, direct rather than indirect evidence would be desirable to show that H.M. can name canonical versions of the present erroneous objects depicted in isolation.

H.M.'s object identification errors were not due to poor-quality depictions of the erroneous objects in What's-Wrong-Here drawings. First, the depictions were the same for H.M. and the controls. Second, normal individuals encountering ambiguities of form typically produce spontaneous comments such as "That's either an apple or a peach" or "That must be a rabbit, but it looks like a dog." However, neither H.M. nor the controls produced such comments.

Finally, H.M.'s uncorrected object identification errors cannot be dismissed as unique events specific to the What's-Wrong-Here task: H.M. has produced similar object identification errors without correction when describing pictures of complex scenes in other studies (see MacKay, James, Hadley, & Fogler, 2008b). In short, H.M.'s uncorrected object identification errors point to a visual cognition deficit that is more general than that shown by the What's-Wrong-Here task.

This is not to say that H.M. cannot recognize familiar pictures of dogs, rabbits, windows, and trash cans when presented in isolation (as occurs with visual agnosia following encephalitic cortical lesions; see e.g., McCarthy & Warrington, 1990). As Milner et al. (1968) point out, H.M. exhibits not just normal, but "superior performance" in recognizing familiar visual objects in isolation (see also Kensinger et al., 2001). In short, to comport with all available data, H.M.'s visual cognition deficit must reflect difficulty in recognizing both unfamiliar visual objects (e.g., a dysfunctional door) and familiar objects that appear in unfamiliar visual contexts (e.g., a partially occluded trash can in a complex classroom scene).

Present findings in relation to empirical generalization H.M.

In summary, we have discussed 12 hypotheses for explaining available data from Experiment 1 and related studies such as Milner et al. (1968) and MacKay et al. (2008b): failure to remember the instructions; miscomprehension of the instructions; lack of motivation; a visual acuity deficit; general slowness; motoric difficulties in circling erroneous objects; a working-memory deficit; unintended speech errors; temporary retrieval failure; poor-quality depictions of the erroneous objects; and a visual cognition deficit involving difficulty in recognizing visual objects only when they are unfamiliar or appear in unfamiliar visual contexts or scenes. Table 2 summarizes these hypotheses in relation to the present findings (with 1 indicating a finding readily explained under a hypothesis, 0 indicating not readily explained under a hypothesis, and N/A indicating not applicable to a hypothesis). As can be seen in Table 2, a visual cognition deficit involving unfamiliar objects and familiar objects in unfamiliar visual contexts readily explains all available findings, whereas 10 of the remaining hypotheses readily explain 0–50% of available findings, and 1 explains 67% of available findings. A visual cognition deficit involving unfamiliar objects and familiar objects in unfamiliar visual contexts therefore provides the strongest account of available results.

Empirical generalization H.M. accurately characterizes the nature of H.M.'s deficits established in prior studies and his visual cognition deficit established in the present study. Under empirical

TABLE 2
Relations between 12 explanatory hypotheses and the findings requiring explanation in Experiment 1 and related studies

<i>Explanatory hypotheses</i>	<i>Findings requiring explanation</i>		
	<i>Overall What's-Wrong-Here deficit</i>	<i>Uncorrected object identification errors</i>	<i>Familiar object recognition in isolation</i>
Lack of motivation	0	0	0
Visual acuity deficit	0	0	0
Failure to remember the instructions	0	N/A	0
Miscomprehension of the instructions	0	N/A	0
Temporary retrieval failure	N/A	0	0
Unintended speech errors	N/A	0	N/A
Poor-quality depiction (of erroneous objects)	0	0	1
Deficits in explicit learning and memory for unfamiliar information	0	N/A	N/A
General slowness	1	0	N/A
Motoric difficulties (in circling erroneous objects)	1	0	N/A
Working-memory deficit	1	0	1
Visual cognition deficit (involving unfamiliar objects and familiar objects in unfamiliar visual contexts)	1	1	1

Note. 1 indicates readily explained; 0 indicates not readily explained; and N/A indicates not applicable to a hypothesis.

generalization H.M., *H.M. exhibits impaired processing of never-previously encountered information* (e.g., an unfamiliar visual object such as an erroneous door) *and impaired processing of familiar information in unfamiliar or never-previously encountered contexts* (e.g., a familiar visual object such as a rabbit in an unfamiliar visual context such as a haunted house), *but spared processing of familiar information in familiar contexts encountered frequently before and after his lesion* (e.g., familiar objects presented in isolation).

H.M. therefore exhibits parallel deficits in visual cognition and sentence comprehension under empirical generalization H.M. For example, just as H.M. has difficulty identifying visual errors in What's-Wrong-Here scenes, H.M. has difficulty identifying linguistic errors in ungrammatical sentences such as *Every Friday our neighbor wash her car* (see MacKay et al., 2007). Similarly, just as H.M. can readily identify familiar objects in isolation but not in unfamiliar visual contexts, H.M. can comprehend familiar words such as *crush* in isolation but not in unfamiliar sentence contexts such as *She is easily crushed* (see MacKay et al.).

The internal representation hypothesis

Empirical generalizations are of course descriptive rather than explanatory in nature, and the internal representation hypothesis postulates explanatory mechanisms to account for empirical generalization H.M. (see MacKay et al., 1998a; MacKay & James, 2001, 2002; MacKay et al., 2007; and MacKay et al., 1998b). These mechanisms explain why H.M.'s lesion has made it difficult for him to form an accurate internal representation for comprehending, recognizing, and retrieving or producing unfamiliar or never previously encountered information, and for comprehending, recognizing, and retrieving or producing familiar information within unfamiliar or never-previously encountered contexts.

Applying these mechanisms to the present results, H.M. exhibited an overall deficit in detecting erroneous objects in What's-Wrong-Here pictures because he had difficulty forming an accurate internal representation for the novel or unfamiliar aspects of visual objects such as erroneous doors. Similarly, H.M. produced object identification errors because he had difficulty forming an accurate internal representation for never-previously encountered contexts or scenes containing familiar visual objects—for example, a rabbit in a haunted-house scene. Moreover, H.M. failed to correct object identification errors such as calling a rabbit a dog because he lacked an accurate internal

representation of the rabbit for comparison with his erroneous descriptor.

However, H.M. can readily comprehend and recognize familiar visual objects such as a rabbit in isolation because he formed an accurate internal representation for rabbits as a child and has used that representation frequently before and after his lesion. H.M.'s problem in the present task arose in the process of integrating already-formed representations for familiar objects with an internal representation for unfamiliar scenes. This same internal representation problem has thwarted attempts to program computers to recognize simple objects in everyday scenes or contexts. As Minsky (2006) points out (p. 149), "the seeming 'directness' of seeing the world is an illusion that comes from our failure to sense the complexity of our own perceptual machinery." This perceptual machinery involves bottom-up and top-down interactions and binding between lower level feature-detectors and higher level scene describers, scene-analyzers, and object-finders, consistent with structural aspects of visual system neuroanatomy. For example, the lateral geniculate nucleus receives about 80% of its fiber inputs top-down from the cortex and only 20% bottom-up from the retinas (Minsky, pp. 152–153).

Other explanatory accounts

As noted earlier, forming an accurate internal representation for an erroneous object is only the first step in error detection, and H.M.'s overall deficit on the What's-Wrong-Here task could in principle reflect problems with comparison processes (e.g., for comparing the internal representation for a normal or canonical door versus the dysfunctional door in Figure 1b) or with inference processes (e.g., underlying the decision that a dysfunctional classroom door represents an erroneous object). However, without further research, these hypotheses are implausible because none of the many prior studies with H.M. have reported impaired comparison or inference processes involving any type of information, including spatial information. Moreover, Experiment 2 will provide direct evidence that comparison and inference processes involving visual forms are intact in H.M.

EXPERIMENT 2: THE HIDDEN-FIGURE TASK REVISITED AND EXTENDED

Experiment 2 used a different type of task to test the internal representation hypothesis outlined in Experiment 1 and to test the applicability of empirical generalization H.M. to visual cognition. The task was a modified version of the Thurstone

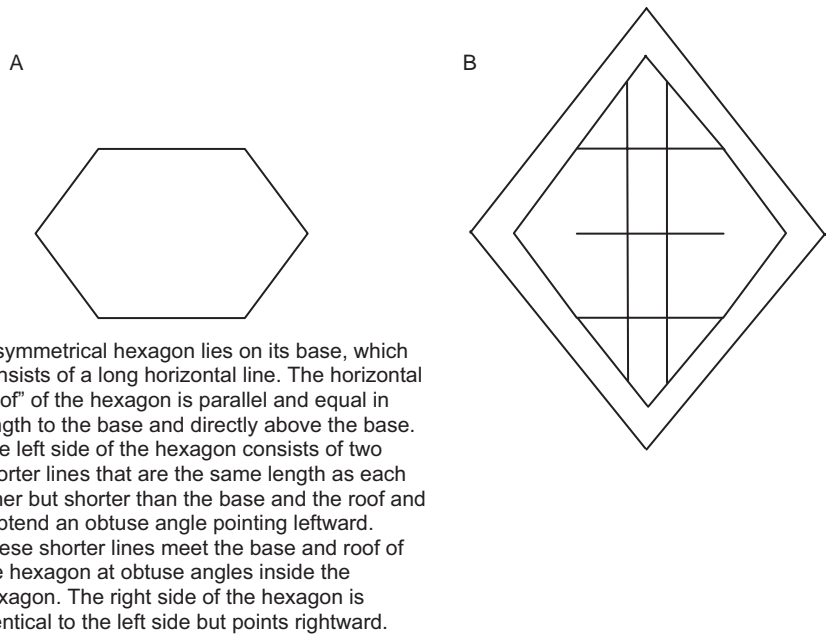


Figure 2. (A) A typical unfamiliar target from single-target subtests of the Thurstone (1949) Hidden-Figures Test (Experiment 2), together with one possible verbal description of critical visual features of this target. (B) The concealing array for the target in B.

(1949) Hidden-Figures Test that compared H.M.'s ability to detect two types of targets in concealing arrays: unfamiliar targets with few or no prior encounters (see Figures 2a and 2b for a relatively simple example) versus familiar targets with many prior encounters in everyday life (see Figures 3a–3f for examples).

Under the internal representation hypothesis, children acquire two types of stable internal representations for familiar or frequently encountered targets such as the circles, squares, and right-angle triangles in Figures 3a–3f: a visual or spatial representation and a verbal representation—that is, descriptors such as "a circle," "a square," or "a triangle."

In contrast, no one is likely to acquire at any time in their lives permanent verbal and spatial internal representations for unfamiliar forms such as Figure 2a and all other targets in the Thurstone (1949) test. By way of illustration, naïve participants are unlikely to have stored the following verbal representation for Figure 2a: "This figure is a symmetrical hexagon that lies on its base, which consists of a long horizontal line. The horizontal 'roof' of the hexagon is parallel and equal in length to the base and lies directly above the base. The left end of the hexagon consists of two shorter lines that are the same length as each other but shorter than the base and roof and subtend an obtuse angle pointing leftward. These shorter lines meet at the base and roof and subtend an obtuse angle

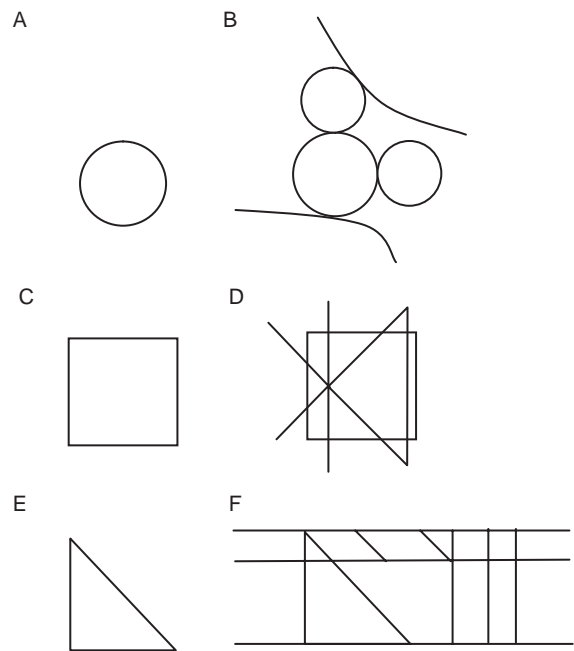


Figure 3. Left column (A, C, E): The familiar targets in Experiment 2. Right column (B, D, F): Typical concealing arrays that contain them.

pointing leftward. These shorter lines meet the base and roof of the hexagon at obtuse angles inside the hexagon. The left and right ends of the hexagon are identical except that the right end points rightward." This long and complicated

narrative of course represents only one of many possible verbal descriptions for accurately characterizing Figure 2a. The unfamiliar concepts summarized in this narrative nonetheless suggest by analogy that this figure also lacks a permanent internal representation in spatial memory.

Under empirical generalization H.M. and the internal representation hypothesis, H.M. is unlikely to exhibit deficits in detecting familiar targets (circles, squares, and right-angle triangles) because he formed an internal representation for these visual forms well before his age 26 lesion and has used that internal representation frequently since then. By contrast, H.M. is likely to exhibit deficits in detecting unfamiliar targets for which he must form a new internal representation, the locus of his deficit under the internal representation hypothesis.

As a subsidiary issue, Experiment 2 also addressed the Milner et al. (1968) assumption that H.M.'s hidden-figure deficits reflect his well-known long-term memory problems and not a problem with visual cognition per se. This assumption is relevant to dual-target but not single-target subtests of the Thurstone (1949) Hidden-Figures Test. In dual-target subtests, two target figures appear above 7–10 sets of overlapping and interwoven lines or concealing arrays. Each concealing array contains only one of the targets, and the goal is to trace as many targets as possible within the time limit specified for the subtest. The best detection strategy in dual-target subtests therefore involves storing both targets in memory, with retrieval of the appropriate target triggered via feature matches within the concealing array. This contrasts with single-target subtests, where a single target is continuously available to perception next to its concealing array (see Figures 2a and 2b), with no need for retrieval of an internal representation. If storing and retrieving dual targets represents the sole basis for H.M.'s hidden-figure deficits as per Milner et al. (1968), H.M. should therefore exhibit deficits on dual-target but not single-target subtests of the Hidden-Figure Task in Experiment 2.

Method

Participants

H.M. was tested in 1998 at age 72. The memory-normal controls were the same as those in Experiment 1. However, because of an experimental error, Controls 1 and 2 in Experiment 1 were not run in the familiar dual-target condition. We therefore replaced these controls with 2 additional

participants who matched H.M. as closely as possible in age, background (unskilled and semiskilled labor), IQ, native language, and highest educational degree (see the background characteristics of Controls 5 and 6 in Table 1). The controls had mean age 68.75, mean Performance and Verbal IQ 113.38, and the high-school degree as highest educational level.

Materials

The materials consisted of eight pages, with typed instructions heading each page—for example, “Find the target figure in each drawing below and trace it with the marker provided. Trace only one figure in each drawing.” The Thurstone (1949) Hidden-Figures Test constituted pages 1–6. Page 1 provided practice examples to ensure task comprehension. Pages 2–6 contained the five subtests labeled Part I–V. Part I appeared on page 2 and contained 27 different targets vertically arranged on the left (as in Figure 2a), each embedded within a concealing array to its right (as in Figure 2b). Part II appeared on page 3, and contained a single target above 7 concealing arrays that each contained the target. Part III appeared on page 4 and resembled Part II except that 2 targets appeared above the 7 concealing arrays, which each contained one or the other of the targets. Parts IV and V appeared on pages 5–6 and resembled Part III except that 2 targets appeared above 10 concealing arrays, which each contained one or the other of the targets. Parts I and II in Thurstone were the single-target subtests for comparison with the dual-target subtests (Parts III–V in the Thurstone task).

Two familiar target conditions appeared on pages 7–8. Page 7 resembled Part II of Thurstone (1949) except that the target was familiar: a circle that appeared above six concealing arrays containing the target embedded among, for example, circles with different diameters (see Figures 3a and 3b). Part II of Thurstone served as the single-target unfamiliar condition for comparison with the single-target familiar condition because both conditions had identical instructions and structure (a single target above a set of concealing arrays).

Page 8 was a dual-target condition that resembled Part III of Thurstone (1949) except that both targets were familiar: a square (see Figure 3c) and a triangle (see Figure 3e). These familiar targets appeared above seven concealing arrays that each contained only one of the targets (see Figure 3d and 3f). Part III in Thurstone served as the dual-target unfamiliar condition for comparison with the dual-target familiar condition because both

conditions had the same instructions and structure (two targets above a set of concealing arrays).

Procedure

Procedures resembled Thurstone (1949) except that the experimenter read aloud the instructions that headed each page and asked for questions before starting the timer (thereby ensuring comprehension of the instructions). Time limits were the same as those in Thurstone: 2 minutes for Part I, 1 minute for Part II, 3 minutes for Part III, and 4 minutes each for Parts IV and V. The single-target familiar condition had the same 1-minute time limit and the same instructions as Part II (the single-target unfamiliar condition). The dual-target familiar condition had the same 3-minute time limit and instructions as Part III (the dual-target unfamiliar condition).

The controls took the Thurstone (1949) test for the first and only time in the present study whereas H.M. took this test on many prior occasions (see e.g., Corkin, 1979). However, neither H.M. nor the controls received prior practice with the familiar target conditions in Experiment 2.

Results

Main results

Table 3 shows the number of correctly traced targets for H.M. and the memory-normal controls (means with *SDs*) in the full Thurstone (1949) task, in the single-target unfamiliar condition (Part II in Thurstone), in the single-target familiar condition, in the dual-target unfamiliar condition (Parts III–V in Thurstone), and in the dual-target familiar condition.

Overall performance on the Thurstone (1949) test. The overall mean number of correctly traced embedded targets was 28.75 for the controls

(*SD* = 5.50) versus 7.00 for H.M., a reliable deficit of 3.95 standard deviations (see Table 3).

Performance with familiar versus unfamiliar targets. In the unfamiliar target conditions (Parts II–V in Thurstone, 1949), the mean number of correctly traced targets was 14.75 (*SD* = 2.22) for the controls versus 2.00 for H.M. (see Table 3), a reliable deficit of 5.74 standard deviations. In the (corresponding) familiar target conditions, the mean number of correctly traced targets was 11.50 for the controls (*SD* = 1.00) versus 10.00 for H.M. (see Table 3), a nondeficit.

Alternate statistical procedures. As an alternate means of determining whether H.M., as a single observation for any condition, lies outside the population distribution for the control participants, we derived prediction intervals for our main results, calculated as $t(N - 1) = (\text{H.M.} - \text{the control mean}) / [\text{SD for the controls} \times \text{square root}(1 + 1/N)]$, where *N* is the number of control participants (see e.g., Meade & Islam, 1995).

For the overall number of correctly traced embedded targets, the prediction interval was reliable at $p < .05$, $t(3) = -3.53$. H.M.'s overall performance on the Thurstone (1949) test therefore lay outside the population distribution for the control participants, replicating our main analysis.

For performance in the unfamiliar conditions in Table 3 (Parts II–V in Thurstone, 1949), the prediction interval was reliable at $p < .01$, $t(3) = -5.12$. H.M.'s performance in the unfamiliar conditions therefore lay outside the population distribution for the controls, again replicating our main analysis. For performance in the corresponding familiar conditions in Table 3, the prediction interval was nonreliable, $p > .05$, $t(3) = -1.82$, again replicating our main analysis. The main results in Experiment 2 therefore held for both standard and nonstandard (prediction interval) statistics.

TABLE 3

Number of correctly traced targets in Experiment 2 for H.M. and the controls for the full Hidden-Figures Test and for the single- and dual-target unfamiliar versus familiar conditions

Participants	Full Hidden-Figures Test	Single-target condition		Dual-target condition	
		Unfamiliar ^a	Familiar	Unfamiliar ^b	Familiar
H.M.	7.00	0.00	6.00	2.00	4.00
Controls	28.75 (5.50)	3.75 (1.50)	6.00 (0.00)	11.00 (0.82)	5.50 (1.00)

Note. Means (with *SDs*) for the full Hidden-Figures Test (Thurstone, 1949). See text for explanation.

^aPart II in Thurstone. ^bParts III–V in Thurstone.

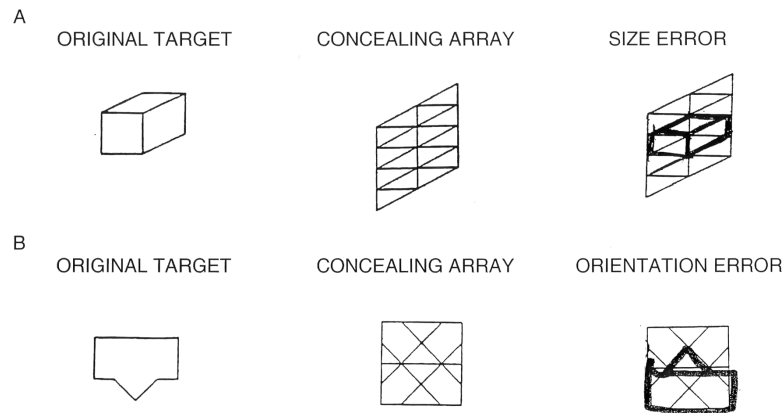


Figure 4. A typical size error, where a participant (here a control) traced a form in a concealing array that resembled the target in shape but not size. The target appears to the left, the original concealing array in the center, and the error to the right. (B) A typical orientation error, where a participant (here H.M.) traced a form in a concealing array that was identical to the target in shape but not in orientation. The target appears to the left, the original concealing array in the center, and the error to the right.

Performance on single- versus dual-target unfamiliar subtests. Comparing within-subject performance for the absolute number of correctly traced single-versus dual-target stimuli in Thurstone (1949; Parts I–V) was problematic because the single-versus dual-target conditions differed in mean number of possible correct responses (17.00 vs. 9.00, respectively) and mean time per condition (1.50 min vs. 3.67 min, respectively). However, relative to the controls, H.M. exhibited reliable deficits for both single- and dual-target subtests and smaller deficits in single- than dual-target subtests. The number of correctly traced targets for the single-target unfamiliar subtests was 5.00 for H.M. versus a mean of 17.75 for the controls ($SD = 4.92$), a reliable deficit of 2.59 standard deviations. The number of correctly traced targets for the dual-target unfamiliar subtests was 2.00 for H.M. versus a mean of 11.00 for the controls ($SD = 0.82$), a reliable deficit of 10.98 standard deviations. H.M.'s deficits were therefore 8.59 standard deviations smaller in single- than in dual-target subtests.

Subsidiary results

Size errors. Size errors were scored when participants traced forms in the concealing arrays that were identical to a target in shape but not size (see Figure 4a for a typical example). Size errors occurred about equally often for H.M. ($N = 2.00$) and the controls ($M = 2.00$; $SD = 1.63$).

Orientation errors. Orientation errors were scored when participants traced forms in the concealing arrays that were identical to a target in shape but not orientation (see Figure 4b for a typical example). Orientation errors did not differ

reliably in frequency for H.M. ($N = 1.00$) versus the controls ($M = 0.25$; $SD = 0.50$), although the small number of orientation errors should be noted.

Target-unrelated errors. Target-unrelated errors were scored when participants traced embedded figures that bore no resemblance to the targets (see Figures 5a–5d for examples). Target-unrelated errors were reliably more common for H.M. ($N = 4.00$) than for the controls ($M = 0.25$; $SD = 0.50$), a difference of 7.50 standard deviations. H.M. only produced this remarkable type of error for unfamiliar targets.

Target-tracing errors. Target-tracing errors were scored when participants traced lines in the target itself in addition to or instead of in the concealing array (see Figure 6 for an example). Target-tracing errors were more common for H.M. ($N = 3.00$) than for the controls ($M = 0.00$; $SD = 0.00$), a reliable difference in excess of 6.00 standard deviations. H.M. only produced this remarkable type of error for unfamiliar targets.

Generalizability of the present results. To determine whether the present results generalize to a larger control group ($N = 10$) that was less well matched with H.M. for IQ, we ran 6 additional memory-normal controls and combined their data with the available data for Controls 3–6 in Experiment 2.¹ The mean IQ of all 10 controls in this study was 117.00 ($SD = 4.96$), their mean age was 70.30 ($SD = 3.43$), their native language was

¹The 6 new controls included 2 who were run in all but the familiar target conditions.

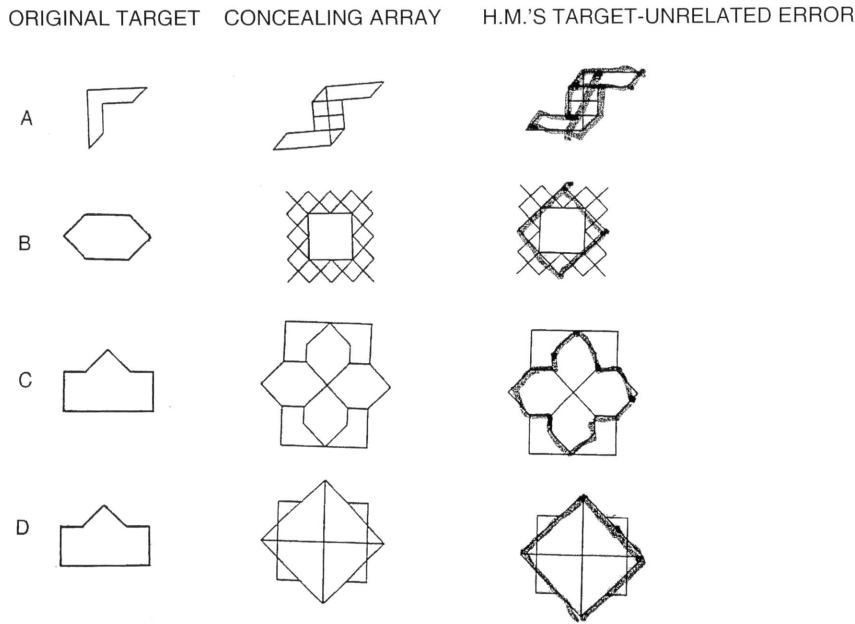


Figure 5. (A–D): Target-unrelated errors, where H.M. traced embedded figures unrelated to the target. The original concealing arrays appear in the center, the targets to the left, and H.M.'s target-unrelated errors to the right.



Figure 6. A target-tracing error (shown on the right), where H.M. traced part of the original target (shown to the left) and added extra lines.

English, their background was skilled or semi-skilled labor, and their highest educational level was the high-school degree. On average, the mean IQ score for these less well-matched controls was 5 points higher than that for H.M.

Table 4 shows the number of correctly traced targets for H.M. and the less well-matched memory-normal controls (means with *SDs*) in the full Thurstone (1949) task, in the single-target unfamiliar condition (Part II in Thurstone), in the single-target familiar condition, in the dual-target unfamiliar conditions (Parts III–V in Thurstone), and in the dual-target familiar condition. As in the main experiment, H.M. exhibited a reliable deficit of 2.36 standard deviations relative to the controls for the overall mean number of correctly traced unfamiliar targets on the full Thurstone test (Parts I–V; see Table 4), a reliable deficit of 2.10 standard deviations in the dual-target unfamiliar subtests (Parts III–V), and a reliable deficit of 5.74 standard deviations in the (combined) unfamiliar target subtests (Parts II–V), with no reliable deficit in the

(combined) familiar target conditions (see Table 4). Unlike in the main experiment, however, H.M. exhibited a nonreliable deficit of 1.94 standard deviations in the single-target unfamiliar subtests (Parts I–II). In short, our follow-up study replicated all earlier results except that H.M. exhibited reliable deficits in both single- and dual-target unfamiliar subtests relative to the closely matched controls in the main experiment but only exhibited a reliable deficit in dual-target unfamiliar subtests relative to the less closely matched controls in our follow-up study. Although minor, this difference illustrates the importance of closely matched controls.

Discussion

Four basic findings in Experiment 2 require explanation: H.M.'s overall deficit relative to carefully matched controls on the full Thurstone (1949) test; H.M.'s selective deficits for unfamiliar but not

TABLE 4

Number of correctly traced targets in Experiment 2 for H.M. and Controls 1–10 for the full Hidden-Figures Test and for the single- and dual-target unfamiliar versus familiar conditions

Participants	Full Hidden-Figures Test	Single-target condition		Dual-target condition	
		Unfamiliar ^a	Familiar	Unfamiliar ^b	Familiar
H.M.	7.00	0.00	6.00	2.00	4.00
Controls 1–10	24.00 (7.21)	3.80 (2.04)	6.00 (0.00)	9.20 (3.43)	5.67 (0.82)

Note. Means (with *SDs*) for the full Hidden-Figures Test (Thurstone, 1949). See text for explanation.

^aPart II in Thurstone. ^bParts III–V in Thurstone.

familiar targets; H.M.'s smaller deficits for single- than for dual-target subtests; and H.M.'s selective deficits involving some error types but not others. We first address some implausible hypotheses for explaining these findings. We then discuss how these findings bear on empirical generalization H.M. and the internal representation hypothesis.

H.M.'s overall deficit

H.M.'s deficit of 3.95 standard deviations relative to carefully matched controls in detecting unfamiliar hidden figures on the full Thurstone (1949) test remained robust across different statistical procedures and generalized to the less well-matched controls in our follow-up study. The size of H.M.'s deficit was nonetheless surprising in view of H.M.'s extensive prior practice with the Thurstone test. Without this extensive prior practice (which the controls did not receive), even larger deficits could be expected because practice without feedback facilitates hidden-figure detection (see e.g., Djang, 1937; Hanawalt, 1942) and facilitates H.M.'s performance in particular in a wide range of tests (see MacKay et al., 2007).

H.M.'s overall deficit was unrelated to comprehension and/or memory for the instructions because H.M. understood and followed the same instructions without deficits in the familiar target conditions. Nor was H.M.'s overall deficit due to motoric slowing or insufficient time to trace the targets: Contrary to a motoric slowing hypothesis, H.M. exhibited target tracing deficits in unfamiliar but not familiar target conditions even though both conditions had the same allotted time for target tracing.

H.M.'s overall deficit was likewise not readily explained under a forgetting hypothesis whereby H.M. encoded but forgot or failed to maintain (aspects of the) targets in memory during a subtest. Contrary to this forgetting hypothesis, H.M. forgets at the same rate as control participants if initial learning is equated in recognition memory tasks (see Freed, Corkin, & Cohen, 1987); the

target and concealing arrays were available to perception throughout each trial in Experiment 2 so as to prevent forgetting; and if forgetting occurred, it was target specific: H.M.'s nondeficits in the familiar target conditions indicate that some targets were not forgotten.

Nor was H.M.'s overall deficit due to a problem in scanning the targets, in scanning the concealing arrays, or in scanning from targets to concealing arrays. If the unfamiliar conditions required these hypothetical scanning processes, then so did the corresponding familiar conditions. However, H.M. exhibited deficits in the unfamiliar but not familiar conditions.

Nor was H.M.'s overall deficit due to a general problem in comparing or matching the targets and concealed targets. Because both familiar and unfamiliar targets required identity matches, a general matching difficulty cannot explain why H.M. exhibited deficits for unfamiliar but not familiar targets. Nor can a general matching difficulty explain why H.M. exhibited selective error deficits involving shape but not size or orientation because correct responses required a match on all three dimensions (size, orientation, and shape).

Nor was H.M.'s overall deficit due to his well-established problems with explicit learning and recall of unfamiliar episodic and semantic information. Like detecting erroneous objects in What's-Wrong-Here scenes, detecting hidden figures requires neither explicit learning nor explicit recall: Participants were not explicitly instructed to learn and remember either the targets or the concealing arrays, and explicit recall of unfamiliar or never previously encountered targets is impossible in principle.

Selective deficits for familiar but not unfamiliar targets

H.M. exhibited a reliable deficit of 5.74 standard deviations in the unfamiliar target conditions (Part II–V in Thurstone, 1949), but no reliable deficit in the corresponding familiar target conditions, a remarkable pattern because H.M. received extensive

prior exposure to the unfamiliar target conditions but encountered the familiar target conditions for the first time in Experiment 2. As noted earlier, H.M.'s selective deficits for unfamiliar but not familiar targets ruled out several possible accounts of the present results: miscomprehension and/or forgetting of the instructions; motoric slowing; forgetting or failure to maintain a target in memory; tracing difficulty; visual scanning problems; and form-matching problems.

Smaller deficits for single- than for dual-target unfamiliar subtests

For unfamiliar targets (Parts I–V in Thurstone, 1949), H.M. exhibited reliable deficits for both single- and dual-target subtests, contradicting the Milner et al. (1968) assumption that H.M. only exhibits hidden-figure deficits on dual-target subtests.

However, H.M.'s deficits were 8.59 standard deviations smaller in single- than in dual-target unfamiliar subtests. Under one hypothesis, this difference reflects forgetting or difficulty in maintaining multiple targets in memory during target search. However, this hypothesis suffers from the same problems as the more general forgetting hypothesis discussed earlier. For example, H.M. clearly remembered or maintained some multiple targets in memory because he was deficit free in the dual-target familiar condition.

The selective nature of H.M.'s error deficits

H.M. exhibited selective deficits involving some error types (target-unrelated errors where H.M. traced figures bearing no resemblance to the target; see Figures 5a–5d; and target-tracing errors where H.M. drew on the target itself in addition to or instead of the concealing array; see Figure 6) but not other error types (size errors as in Figure 4a and orientation errors as in Figure 4b).

Such selective error deficits are difficult to explain under a forgetting hypothesis. For example, a tendency to forget or fail to maintain a target in memory while scanning the concealing arrays cannot explain either H.M.'s deficits for target-unrelated and target-tracing errors or his nondifficulties for size and orientation errors. A forgetting hypothesis is also implausible as the sole cause of H.M.'s target-unrelated errors for reasons noted earlier: H.M. forgets at the same rate as control participants if initial learning is equated in recognition memory tasks (see Freed et al., 1987); the target is available to perception throughout each trial of our Hidden-Figure task so as to prevent forgetting; and a general forgetting hypothesis cannot explain why target-unrelated errors involved unfamiliar but not familiar targets.

Experiment 2 results in relation to empirical generalization H.M.

Under one aspect of empirical generalization H.M., H.M. exhibits impaired processing of never-previously encountered information. Two basic findings in Experiment 2 were consistent with this aspect: H.M.'s overall deficit relative to carefully matched controls on the full Thurstone (1949) test; and the target-unrelated and target-tracing errors involving unfamiliar targets that H.M. produced reliably more often than the controls. Under a second aspect of empirical generalization H.M., H.M. exhibits spared processing of familiar information encountered frequently before and after his lesion. Two basic findings in Experiment 2 were consistent with this second aspect: H.M. detected familiar targets without deficit, and he produced no target-unrelated, target-tracing, size, or orientation errors involving familiar targets.

The internal representation hypothesis

Under the internal representation hypothesis outlined in Experiment 1, H.M. has difficulty in forming an internal representation for novel or unfamiliar visual objects encountered for the first time—for example, an erroneous door. However, H.M. can readily activate the already-formed internal representation for familiar visual objects in familiar contexts—for example, a normal or canonical door presented in isolation.

This internal representation hypothesis readily explains the five basic results in Experiment 2. If H.M. has difficulties in forming an internal representation for unfamiliar but not familiar visual forms, then deficits for unfamiliar but not familiar targets in our Hidden-Figure task can be expected. Similarly, if H.M. has difficulty in forming an internal representation for unfamiliar targets, then deficits for both single- and dual-target unfamiliar subtests can be expected. Moreover, larger deficits can be expected for dual-target unfamiliar subtests requiring the formation of two new internal representations: If forming one novel internal representation is difficult, forming two novel internal representations will be more difficult.

The internal representation hypothesis also readily explains the target-unrelated errors that only H.M. produced and only for unfamiliar hidden targets: Under this hypothesis, H.M. traced target-unrelated forms (as in Figures 5a–5d) because he lacked the internal representation that normally guides and constrains responses involving unfamiliar targets. By contrast, H.M. produced no target-unrelated errors involving familiar targets (circles, triangles, and squares) because a

readily retrieved internal representation that he formed as a child and has used frequently since then guided and constrained his responses to familiar targets under the internal representation hypothesis.

The internal representation hypothesis also suggests two possible accounts that together explain all aspects of H.M.'s target-tracing errors (where H.M. traced lines in an unfamiliar target itself in addition to or instead of in the concealing array; see Figure 6). Under one account, target tracing engages a process analogous to verbal rehearsal or repeated activation of components essential for an internal representation. Because such rehearsal or repeated activation represents an inefficient but effective means whereby H.M. can form novel internal representations (see MacKay et al., 1998a; MacKay & James, 2001, 2002; MacKay et al., 2008a, 2008b; MacKay et al., 2007; and MacKay et al., 1998b), H.M.'s target-tracing errors reflected an attempt to form internal representations under the internal representation hypothesis. Moreover, H.M. only produced target-tracing errors involving unfamiliar targets because for familiar targets (e.g., circles), a preformed internal representation in H.M.'s long-term visual memory rendered repeated activation or tracing unnecessary. Under the second account, H.M.'s target-tracing errors reflected an attempt to see and successfully trace a target in a "provisional" concealing array where he himself added the concealing lines (see Figure 6).

In summary, we have discussed seven hypotheses for explaining the four basic findings in Experiment 2: failure to comprehend or remember the instructions; motoric slowing or insufficient time to trace perceived targets in the concealing arrays; target forgetting (or failure to maintain a target in memory); deficits in visual scanning; deficits involving

comparison processes; deficits in explicit learning and recall of unfamiliar episodic and/or semantic information; and the internal representation hypothesis. The relations between these hypotheses and the present results are summarized in Table 5, with 1 indicating "can readily explain," 0 indicating "cannot readily explain," and 0.5 indicating "can readily explain with one additional assumption." To illustrate this 0.5 category, the internal representation hypothesis can readily explain H.M.'s nondeficits involving size and orientation with a single additional assumption (setting aside our caveat regarding the small number of orientation errors). Under this assumption, independent mechanisms represent size versus orientation versus shape or form, so that a visual form can be unfamiliar in shape but familiar in size (e.g., small, medium, or large) and orientation (e.g., facing right or facing left). This being the case, H.M.'s nondeficits for size and orientation may reflect activation of familiar size and orientation representations without the need to form new representations (unlike the case for unfamiliar shapes).

As can be seen in Table 5, the internal representation hypothesis readily explained 3.50 or 88% of the present findings, versus 0 (0%) to 1 (25%) for the remaining six hypotheses. Present results therefore overwhelmingly supported the internal representation hypothesis.

Nonetheless, limitations of the present support for the internal representation hypothesis must be stressed. First, H.M. and the controls performed at ceiling in the single-target familiar condition of Experiment 2, rendering H.M.'s performance relative to the controls difficult to interpret in that condition. Fortunately, however, below-ceiling performance in the dual-target familiar condition obviated this problem while addressing the same

TABLE 5
Relations between seven explanatory hypotheses and the findings requiring explanation in Experiment 2

<i>Explanatory hypotheses</i>	<i>Findings requiring explanation</i>			
	<i>Overall deficit</i>	<i>Selective unfamiliar vs. familiar deficits</i>	<i>Larger dual-target than single-target deficits</i>	<i>Selective error deficits</i>
Failure to comprehend or remember the instructions	0	0	0	0
Motoric slowing (insufficient time to trace the targets)	0	0	0	0
Forgetting (or failure to maintain) the targets	0	0	1	0
Visual scanning deficit	0	0	1	0
Comparison processing deficit	0	0	1	0
Deficits involving explicit learning and recall of episodic and semantic information	0	0	0	0
Deficits in forming internal representations for unfamiliar forms	1	1	1	0.5

Note. 1 indicates readily explained; 0 indicates not readily explained; and 0.5 indicates readily explained with an additional assumption.

theoretical issues as those for the single-target familiar condition.

Second, the concealing arrays for single- versus dual-target conditions and for familiar versus unfamiliar target conditions in Experiment 2 may have differed in complexity, and further research seems warranted to control for this factor. Further research on other aspects of the concealing arrays that might have affected H.M.'s hidden-figure performance also seems warranted. For example, under the internal representation hypothesis, H.M. is likely to have greater difficulty than the controls in rejecting "extraneous" forms in concealing arrays that contain some but not all aspects of a target, especially when these "foils" are simpler and more familiar than the target (see Minsky, 2006, for a similar problem in machine vision). Examples of such familiar foils in Figure 2b are a diamond with an elongated vertical axis, an isosceles triangle whose left side is elongated and vertical, an isosceles triangle whose right side is elongated and vertical, and two isosceles triangles meeting at a point in the manner of a bow tie (see Figure 2b). Such foils may have contributed to H.M.'s target-unrelated errors involving unfamiliar targets in Experiment 2.

A third issue for further research concerns the generalizability of H.M.'s visual cognition deficits to other patients with MTL damage. Although no other patient exhibits MTL damage exactly like H.M.'s, available data on this issue comport with the present results. For example, Barense et al. (2005, p. 10245) showed that humans with MTL damage exhibited large deficits in discriminating between novel objects (blobs and barcodes) but not familiar objects (bugs and beasts), possibly reflecting "an inability to perceive or create a representation of such stimuli at the time of encoding" (see also Barense, Gaffan, & Graham, 2007; Lee, Barense, & Graham, 2005a; Lee et al., 2005b).

GENERAL DISCUSSION

Under empirical generalization H.M., H.M. exhibits impaired processing of never-previously encountered information and impaired processing of familiar information in never-previously encountered contexts, but spared processing of massively repeated information and familiar information presented in familiar contexts (MacKay et al., 2007). The initial support for empirical generalization H.M. came from explicit tests of H.M.'s declarative, episodic and semantic memory for novel or never previously encountered information and from implicit memory tests involving unfamiliar pseudowords.

Subsequent support for empirical generalization H.M. came from three sources: sentence comprehension tests, sentence production tests, and tests of H.M.'s ability to read sentences aloud.

The results of Experiments 1 and 2 and related picture-description studies indicate that empirical generalization H.M. also applies to visual cognition. To illustrate, H.M.'s uncorrected object identification errors in Experiment 1 reflect processing difficulties involving familiar information in unfamiliar contexts. Inability to detect a dysfunctional door in a What's-Wrong-Here picture likewise reflects processing difficulties involving never-previously encountered information because H.M. has no prior experience with dysfunctional doors. Inability to detect concealed targets in the Thurstone (1949) task likewise reflects processing difficulties involving unfamiliar information encountered for the first time after H.M.'s lesion. Finally, H.M.'s deficit-free detection of familiar circles, squares, and right-angle triangles in the modified Hidden-Figure task in Experiment 2 reflects processing of familiar information in familiar contexts.

H.M.'s selective deficits in visual cognition cannot be dismissed as reflecting H.M.'s already established deficits involving either language or memory. For example, attributing H.M.'s visual cognition deficits to his already established language comprehension deficits is not an option. As summarized in Tables 2 and 5, results in Experiments 1 and 2 cannot be explained in terms of failure to comprehend or remember the instructions. Attributing H.M.'s visual cognition deficits to his already established memory problems is likewise not an option. As summarized in Tables 2 and 5, results in Experiments 1 and 2 cannot be explained in terms of explicit learning and memory, working-memory limitations, temporary retrieval failures, forgetting (or failure to maintain in memory) the targets in the Hidden-Figure task, or deficits involving explicit learning and recall of episodic and semantic information.

Could H.M.'s visual cognition deficits reflect atrophy to cortical areas beyond the MTL that are known to be involved in higher visual processing—for example, lateral temporal lobe (LTL) regions, including area TE/TEO? Magnetic resonance imaging (MRI) data obtained close to the present time of test suggested (without data from same-age memory normal controls) that H.M. had "possible" but at most "minimal" damage to lateral temporal neocortex that arose after his 1953 MTL ablation (Corkin, Amaral, González, Johnson, & Hyman, 1997). A decade later, follow-up MRI data (Salat et al., 2006) indicated vascular changes and cortical thinning in H.M. of unknown etiology, unknown

time of onset, and unknown relations to behavior relative to 4 memory-normal controls (unmatched with H.M. for IQ, education, or background). Although Salat et al. ruled out Alzheimer-related degeneration, could undetectable or incipient atrophy have caused H.M.'s visual cognition deficits in the present study a decade earlier?

Three main lines of evidence argue against this incipient atrophy hypothesis. First, H.M. performed without deficit for familiar figures on the Hidden-Figures task in Experiment 2, whereas a deficit would be expected with LTL damage (see e.g., Teuber, Battersby, & Bender, 1951). Second, H.M. originally exhibited reliable deficits on memory tasks and hidden-figures tasks at about the same time (1967; see Milner et al., 1968). If H.M.'s hidden-figures deficits reflect cortical atrophy, then his memory deficits could also reflect cortical atrophy. This being the case, however, more than just "possible" or "minimal" damage to H.M.'s LTL would be expected some 30 years later in Corkin et al. (1997). Third, H.M.'s MTL damage and visual cognition deficits comport with recent data indicating that MTL lesions without incipient cortical damage impair visual cognition in humans (see e.g., Barense et al., 2007; Lee et al., 2005a; Lee et al., 2005b) and animals (see e.g., Buckley, 1985; Buckley, Booth, Rolls, & Gaffan, 2001; Bussey & Saksida, 2002; Bussey, Saksida, & Murray, 2002, 2003; Gaffan, 2001).

In conclusion, theories that address H.M.'s condition must explain why H.M. exhibits parallel deficits and sparing in visual cognition, semantic memory, episodic memory, language comprehension, language production, and reading sentences aloud. These parallels lack parsimonious explanation under the standard "systems theory" account in which H.M. exhibits a pure memory deficit, involving systems for episodic, declarative, and semantic memory but no other information-processing systems. Spared aspects of H.M.'s memory, visual cognition, and language are also problematic for the systems theory account. For example, H.M. does not exhibit deficits in memory tasks involving familiar semantic information (e.g., repetition priming with preoperatively familiar words) or frequently repeated semantic information (see Gabrieli et al., 1988; Keane et al., 1987; Keane et al., 1995; MacKay, 2006; MacKay et al., 1998a; MacKay et al., 2007; O'Kane et al., 2004).

As noted earlier, forming an internal representation involves implicit learning, and under one hypothesis, independent systems house the mechanisms for implicit learning versus whatever information is undergoing implicit learning. However, contrary to this "independent system hypoth-

esis," H.M.'s implicit learning ability clearly depends on the information undergoing implicit learning: H.M. exhibits implicit-learning deficits when processing unfamiliar pseudowords but not when processing preoperatively familiar words (see Gabrieli et al., 1988), just as he exhibits implicit-learning deficits when processing unfamiliar but not familiar visual forms (see Experiment 2).

In general, labels such as "amnesic," "memory deficit," or even "implicit memory deficit" are unhelpful for understanding selective deficits involving implicit memory or any other type of information processing. Labels such as "memory task" or "visual cognition task" are likewise unproductive for understanding the processes and mechanisms underlying performance in any particular task because all higher cognitive tasks involve memory in some form at either encoding or retrieval or both. Moreover, even labels such as "primarily memory task" or "primarily visual task" (see e.g., Lee et al., 2005a; Lee et al., 2005b) are unhelpful for understanding selective deficits, especially selective deficits resembling H.M.'s that span many cognitive domains.

The parallels between language, memory, and visual cognition summarized in empirical generalization H.M. call for a theory in which bilateral MTL damage can interfere with the process of forming internal representations for a wide range of different types of unfamiliar or never previously encountered information, and we have proposed such a theory (see e.g., MacKay, 1990; MacKay et al., 2007). Under this "binding theory," the resolution for the ongoing "either-or" debate concerning the MTL as a memory structure (see e.g., Spiers et al., 2001; Tulving & Markowitsch, 1998) versus a perceptual structure (see e.g., Lee et al., 2005a; O'Keefe & Nadel, 1978) is "both-and."

To summarize the basics of binding theory, various MTL structures such as the hippocampus contain substructures that specialize in helping to form different types of novel internal representations in the cortex, including various types of language representations, visual cognition representations, and representations classically labeled "memory." As a consequence, subdivisions within the hippocampus can make distinct contributions to new memory formation (see Zeineh, Engel, Thompson, & Bookheimer, 2003), different structures within the MTL can subservise different aspects of memory processing (e.g., Aggleton & Brown, 1999; Barense et al., 2005; Brown & Aggleton, 2001; Mishkin, Suzuki, Gadian, & Vargha-Khadem, 1997), and different neurons in the human MTL can respond selectively to different categories of stimuli (see e.g., Kreiman, Koch, & Fried, 2000).

Of course, damaged binding mechanisms can only explain impaired processing of never-previously encountered information involving scenes and sentences in H.M. and other amnesics with MTL damage. Other aspects of binding theory are required to explain H.M.'s unimpaired processing of massively repeated information and familiar information presented in familiar contexts (see MacKay et al., 2007). Both phenomena have a cortical locus under binding theory: H.M. can retrieve or produce without deficit information that he learned prior to his lesion because familiar information and the activation mechanisms for retrieving familiar information reside in non-MTL areas that are intact in H.M. Similarly, H.M. can learn via massive repetition or rehearsal because of the non-MTL locus of activation mechanisms governing rehearsal, and the resulting "engrainment" or strengthening effects on synaptic connections in the cortex are independent of the MTL. Internal rehearsal and intact engrainment processes can also explain why amnesic patients with MTL damage exhibit spared performance when discriminating between unfamiliar objects with unique or distinctive features but impaired performance when discriminating between unfamiliar objects with nonunique or overlapping feature conjunctions (see Barense et al., 2007; Buffalo, Reber, & Squire 1998; Holdstock, Gutnikov, Gaffan, & Mayes, 2000; Lee et al., 2005a; and Lee et al., 2005b). If basically correct, binding theory or some related theory of human cortical functioning and the MTL (e.g., Wickelgren, 1979) promises to have a profound impact on how we understand human memory, amnesia, and cognition.

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