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A Visually Based Developmental Reading Deficit

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This study describes a developmental reading disability and identifies a deficit of visual perception as the underlying cause. A.H., a university student with apparently normal reading comprehension, was severely impaired in reading aloud isolated words (e.g., *dear* → "pear") and sequences of unrelated words (e.g., *pouch cedar culture jacket* → "cedar pouch jacket culture"). Eight experiments involving several visual presentation conditions convincingly linked her impaired reading performance to a developmental deficit in perceiving the location and orientation of visual stimuli. Four additional experiments demonstrated that A.H. achieves good comprehension for meaningful material by exploiting knowledge-based constraints (e.g., syntactic constraints) to "repair" the errors introduced by her visual system. These results have implications for research on developmental dyslexia, normal reading, and normal vision.

Key Words: cognitive neuropsychology; dyslexia; developmental dyslexia; reading; reading disability; vision; visual localization.

As this special issue attests, recent years have seen a growing interest among cognitive scientists in the study of cognitive deficits. For the most part, this interest has centered on deficits resulting from brain damage in adults whose cognitive functioning was normal prior to some neurological insult. Developmental deficits, in which a cognitive function fails to develop normally, have less often been examined from a cognitive science perspective, despite the fact that these deficits—especially the developmental dyslexias—are of considerable societal concern and have long been major foci of attention in other research communities (e.g., neurology, clinical and educational psychology). One aim of this article is to suggest that developmental cognitive deficits merit greater attention from cognitive scientists, both because of the insights these deficits may offer into normal cognition and because of the contributions cognitive theory and methods may make to the understanding of the deficits, and ultimately to improved diagnosis and treatment.

We report a single-subject study of a young woman, A.H., who presented with a paradoxical pattern of reading performance: Her academic achievement, standardized test scores, and self-report suggested that her reading ability was above average, yet on certain simple reading tasks her performance was severely impaired. We first present a brief case history and describe A.H.'s impaired performance on two reading tasks. We then show that A.H. has a profound but selective developmental deficit in visual perception and present evidence that this perceptual deficit underlies her impaired performance on the reading tasks. Next, we describe several studies exploring how A.H. can show seemingly normal reading comprehension despite her perceptual deficit, and finally we consider the implications of our results for the study of developmental cognitive deficits as well as for research on normal cognition.

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A.H.

A.H. is a right-handed woman with normal visual acuity and visual fields. She has no history of neurological injury or disease, and no abnormalities were apparent on neurological exam, electroencephalogram, or structural magnetic resonance imaging. Throughout her elementary and secondary schooling A.H. was assumed to have some form of learning disability, because she experienced substantial difficulty with spelling, math, and foreign languages. However, her academic performance was otherwise good, and she was not placed in classes for learning-disabled students. After graduating from high school, she entered an academically selective university as a regular undergraduate student, and she completed a bachelor's degree in history in the usual four years. She then entered law school and graduated on schedule after three years.

A.H. was studied in our lab for a period of nearly four years, during which time she was 18–21 years old and an undergraduate university student. In an interview at the beginning of the study A.H. described herself as a very bad speller, and she also reported various difficulties with numbers and mathematics (e.g., difficulty memorizing multiplication tables, difficulty learning her new address and phone number when she entered college). In contrast, she described herself as a good reader, asserting that she had no problems learning to read and had consistently been placed in the most advanced reading groups in elementary school. A.H. also stated that she read a great deal and had no difficulty completing her reading assignments in school. A.H.'s grades and standardized test scores from elementary school through college similarly suggest above-average reading ability. For example, she scored in the 94th percentile on the Verbal section of the SAT (Scholastic Aptitude Test), a challenging test of vocabulary and reading comprehension.

Nevertheless, both A.H.'s academic records and her comments in the initial interview contain occasional hints of potential reading difficulty. For example, on a tenth-grade standardized test report a graphic presentation of vocabulary subtest scores places A.H. at the top of the scale on a Synonyms in Context subtest but at the lower end of the scale on Synonyms in Isolation. Interestingly, A.H. mentioned during the interview that she occasionally failed to recognize familiar words when she encountered them out of context. She also stated that even for material that was not especially challenging, she sometimes had to read sentences or paragraphs more than once before they made much sense. These points take on some significance in light of the results we report.

EXPERIMENTAL STUDIES

We tested A.H.'s reading performance in a variety of tasks with stimuli ranging from individual letters to paragraphs. All tasks were nonspeeded; that is, A.H. was under no pressure to respond quickly. Except where otherwise indicated, the stimulus on each trial remained in view until A.H. completed her response. In some tasks the stimuli were presented on paper, printed in Times Roman, Century Schoolbook, or Courier fonts ranging in size from 12 to 24 points. (These variations had no discernible effect on A.H.'s performance.) In other tasks the stimuli were presented on a computer monitor in a sans serif font, as white characters on a dark background. Unless otherwise indicated, stimuli were presented in lower case characters and were centered on the page or computer monitor. A.H. viewed the computer displays in a lighted room from a distance of approximately 40 cm. At this distance each character subtended approximately 0.5° of visual angle horizontally and between 0.5° and 1° vertically.

For some of the tasks presented to A.H., normal control subjects were also tested. These subjects were undergraduate students at the university attended by A.H., and they were matched to her in age and educational level.

IMPAIRED READING PERFORMANCE

In a preliminary exploration of A.H.'s reading we asked her to read aloud individual words and sequences of unrelated words.

Reading Aloud Individual Words

Stimuli were the names of 144 concrete objects selected from the Snodgrass and Vanderwart (1980) pictures (e.g., *sun, envelope, crown, refrigerator*).[1] A.H. was 100% correct (144/144) in naming the pictures orally, demonstrating that she was familiar with the stimulus words and was able to produce them in spoken form.

The words, which varied in length from 3 to 12 letters, were presented on paper one at a time in random order, and A.H. read each word aloud. The stimulus list was presented three times, once in each of three testing sessions. Four control subjects each read the words aloud once; these subjects collectively made 1 error in 576 trials (0.2%).

A.H., however, erred on 53 of 432 trials (12%) across the three presentations of the list. The 53 errors were distributed over 39 of the 144 stimulus words: 28 words were misread once, 8 were misread twice, and three elicited errors on all three presentations. On some trials A.H. hesitated noticeably before producing a response. However, most responses, both correct and erroneous, were made without hesitation, and A.H. usually seemed unaware of her errors.

Table 1 presents examples of A.H.'s erroneous responses. As the examples illustrate, A.H.'s errors were not restricted to low-frequency words such as *anchor;* she also misread short, high-frequency words such as *dog, pen,* and *hand.* All of the erroneous response words were visually similar to the corresponding stimulus words.

TABLE 1

Examples of A.H.'s Errors in Reading Words Aloud

Stimulus	Response
dog	bog
pen	den
lamp	lamb
snail	nails
chain	cabin
hand	band
nose	noise
church	cherish
apple	appeal

Impaired performance in reading words aloud could conceivably arise from a deficit affecting any of the cognitive processes required by the task. For example, errors could occur in constructing visual or orthographic representations of a stimulus word, matching the stimulus representation to a stored lexical-orthographic representation of a familiar word, retrieving semantic information about the word, or accessing the phonological representation needed to generate a spoken response.

In an effort to narrow the range of possibilities, we asked A.H. to define words as she read them aloud. The question of interest was whether definitions for words read incorrectly would correspond to the stimulus or instead to the erroneous response. For example, if A.H. read dog as "bog," would she define the former or the latter? A definition corresponding to the stimulus *dog* would suggest that A.H. matched the stimulus word to the correct lexical representation, and accessed the appropriate semantic information, but erred in some subsequent process (e.g., retrieving the phonological form of the word). In contrast, a definition appropriate to the response word *bog* would indicate that processing had gone awry prior to accessing the word's meaning, perhaps in constructing a visual or orthographic representation of the visual stimulus, or in matching the stimulus representation to the stored representation of a familiar word.

Stimuli were the 144-word list used in the previous word-reading task and a list of 92 common nouns varying in length from 3 to 8 letters. In one presentation of each list A.H. read the word aloud and then gave a brief definition. In a second presentation of the 92-word list A.H. first gave the definition and then read the word aloud.

The results demonstrated clearly that A.H.'s

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[1] We use italics to indicate visual stimulus words (e.g., *bell*); it should be understood that the words presented to A.H. were not italicized. We use quotation marks for spoken responses and a horizontal arrow for the relationship between stimulus and response. For example, *bell* → "dell" indicates that the visual stimulus word *bell* was read aloud as "dell."

TABLE 2

Examples of A.H.'s Errors in Reading and Defining Words

Stimulus	Reading response	Definition
dog	bog	murky swamp
bone	done	when an activity is completed
pig	dig	to make a hole in the earth
star	tars	when someone puts tar on something
rib	rip	to tear
sun	nuns	Catholic women who have given certain vows
skirt	skit	very short play, usually without props or costumes
dust	dusk	time of day just after the sun sets

word-reading errors arose prior to accessing the meaning of the word. Collapsing across lists, A.H. made reading errors on 75 of the 328 trials (23%), and in all cases her definition matched her erroneous reading response. For example, she read *bread* as "beard," and gave the definition "man's facial hair." (See Table 2 for additional examples.) Twenty-one of the reading errors with corresponding incorrect definitions occurred in the define-then-read presentation of the 92-word list, ruling out the possibility that errors in defining words occurred only because A.H. was confused by hearing her incorrect reading response.[2]

Reading Aloud Word Sequences

In this task A.H. read aloud sequences of four unrelated words (e.g., *peacock comet napkin dolphin*) presented in a horizontal row on a computer monitor. Twenty sequences were created from 80 5- to 7-letter nouns. Words with salient visually similar neighbors were avoided, in order to minimize A.H.'s difficulty with individual words. Words were assigned randomly to sequences and to positions within sequences. Two blocks of 20 trials were presented, with each word sequence appearing once in each block.

On two-thirds of the trials (27/40) A.H. read the words out of sequence (e.g., *peacock comet napkin dolphin* → "peacock napkin comet dolphin"). All but one of the errors involved transposition of adjacent words. In addition to the ordering errors, A.H. misread 13 of the 160 individual words (e.g., *recipe* → "receipt"). On most trials A.H. read the word sequence fluently and seemed unaware that she was making errors.

The results from the individual-word and word-sequence reading tasks raise a number of questions. For example: What is the nature of the underlying deficit? Does this deficit affect A.H.'s reading of material other than isolated words and arbitrary word sequences? If so, what are the implications for understanding A.H.'s seemingly excellent reading comprehension in her academic pursuits and daily life? In the following sections we first consider the nature of the deficit, describing results showing that A.H. is impaired in perceiving the location and orientation of visual stimuli, and arguing that this deficit underlies her impaired performance on various reading tasks, including the individual-word and word-sequence tasks. We then explore A.H.'s apparently normal reading comprehension in light of these arguments.

IMPAIRED VISUAL PERCEPTION OF LOCATION AND ORIENTATION

A.H.'s deficit in visual location and orientation perception has been described in previous publications (McCloskey et al., 1995; McCloskey & Rapp, 2000; see also McCloskey & Palmer, 1996); here we summarize the findings relevant to the present study.

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[2] As one would expect, A.H.'s definitions also matched her reading responses for words she read accurately: She gave an adequate definition for 251 of the 253 words she read correctly (99%).

Impaired Performance in Localizing Visual Stimuli

A.H. showed severely impaired performance on several tasks requiring localization of visual stimuli. In one task she closed her eyes while a small wooden block was placed on a table in front of her. She then opened her eyes and reached for the block with a ballistic movement (i.e., without changing direction in midmovement). When the target was directly in front of her, A.H. reached accurately. However, for targets on her left or right she reached to the wrong side of the table (e.g., right for a target on the left) on two-thirds of the trials (63/96).

Results from other experiments revealed impairment in up/down as well as left/right localization. In one experiment an X was presented on a computer monitor at a position left, right, up, or down from the center of the screen, and A.H. indicated the location of the X by moving a mouse (e.g., move left for a stimulus at the left location). Whereas control subjects performed the task virtually without error, A.H. erred on over half of the left and right stimuli (75/144) and on over one-third of the up and down stimuli (51/144). All of her errors were left/right or up/down confusions (e.g., moving down for a stimulus at the up location).

A.H.'s visual localization deficit was also apparent in tasks requiring localization of multiple visual stimuli relative to one another. In one experiment sequences of 3–5 plastic shapes (e.g., *circle triangle rectangle*) were placed in a horizontal row in front of A.H. While the stimulus sequence remained in view, A.H. reproduced it using her own set of shape tokens. On over half of the trials (16/30) she arranged her tokens in the wrong order; for example, she copied the sequence *square rectangle triangle circle* as square rectangle circle triangle.

Impaired Performance in Visual Orientation Judgments

A.H. also showed impairment in judging the orientation of visual stimuli. In one task an arrowhead (> or <) was presented at the center of a computer screen, and A.H. moved a mouse left or right to indicate the direction the arrowhead was pointing. Although the task was nonspeeded, and the stimulus remained in view until she responded, she erred on 40% of the trials (38/96).

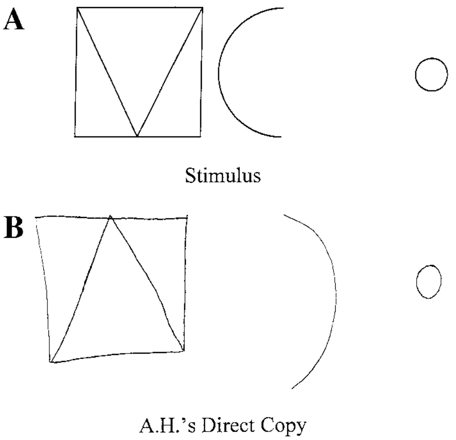
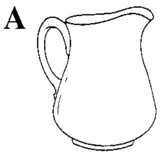


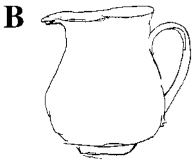
FIG. 1. (A) Stimulus from the Benton Visual Retention Test (Sivan, 1992). From *Benton Visual Retention Test* (Form D, Design 6), by A.B. Sivan, 1992, San Antonio, TX: The Psychological Corporation. *Benton Visual Retention Test,* Fifth Edition. Copyright © 1992 by The Psychological Corporation, a Harcourt Assessment Company. Reproduced by permission. All rights reserved. "Benton Visual Retention Test" is a registered trademark. (B) A.H.'s direct copy, made while the stimulus remained in view.

In several tasks A.H. copied visual stimuli while the stimuli remained in view. These tasks revealed frequent orientation errors, in the form of left–right or up–down reflections. For example, Figure 1A shows a stimulus from the Benton Visual Retention Test (Sivan, 1992), and Figure 1B shows A.H.'s direct copy. A.H. made an up–down reflection in copying one of the two large forms, and a left–right reflection on the other. Figure 2, which shows A.H.'s direct copy of a picture from the Snodgrass and Vanderwart (1980) set, illustrates that orientation errors occurred not only for arbitrary shapes but also for meaningful visual stimuli.

Given that an object's orientation is determined by the locations of its parts relative to one another and to some frame(s) of reference, it seems likely that A.H.'s visual orientation errors stem from the same underlying deficit as her errors in localizing visual stimuli (and evidence discussed below supports this assumption). Accordingly, we refer to the deficit as a



Stimulus



A.H.'s Direct Copy

FIG. 2. (A) Picture from the Snodgrass and Vanderwart (1980) set. (B) A.H.'s direct copy, made while the stimulus remained in view.

visual localization deficit, with the understanding that this term encompasses A.H.'s difficulties with orientation as well as location perception.

Longstanding Impairment

Samples of A.H.'s elementary through secondary schoolwork indicate that the localization deficit was present throughout her school years. For instance, striking mislocalizations and misorientations of people and objects were evident in sketches of paintings A.H. made during high school visits to art museums. The schoolwork errors suggest that A.H.'s impairment may be congenital, especially given the absence of obvious postnatal neurological insult.

Selective Visual Impairment

A.H.'s impairment is a selective deficit of visual perception. In a variety of tasks with nonvisual stimuli her location and orientation judgments were highly accurate. For example, with eyes closed she was uniformly accurate (186/186) in pointing to the source of a sound on her left or right and in drawing an arrow to match the orientation of a wooden arrow she felt by placing her palm over it (32/32). (In contrast, she was wrong half of the time when the arrow was presented visually.) These findings demonstrate that A.H.'s impairment is not a general spatial deficit affecting location and orientation processing across sensory modalities, or a motor deficit affecting the ability to carry out intended movements when making responses.

Other findings argue against the possibility of a visual–motor disconnection in which (accurate) visual location and orientation representations fail to make contact with (perhaps otherwise intact) mechanisms for executing movements. In particular, A.H. was impaired in indicating the location or orientation of visual stimuli even in tasks not requiring spatially directed movements. For example, she was wrong over one-third of the time (24/64) in saying "left" or "right" to indicate the location of an X on a computer monitor. (These errors did not reflect any difficulty with the words *left* and *right,* because verbal left–right responses were uniformly correct in tasks involving auditory or tactile stimuli.) Finally, A.H. showed impairment in tasks with visual stimuli even when her eyes remained fixated during stimulus presentation, indicating that her errors could not be attributed to an eye movement disorder. For example, her error rate was 56% (45/80) in localizing an X to the left or right side of a computer monitor while fixating on a central point. Taken together, the findings from the various visual and nonvisual tasks point clearly to a selective deficit of visual perception.

Effects of Visual Variables

Further evidence that A.H.'s impairment is a visual deficit comes from results showing that her accuracy in perceiving the location and orientation of visual stimuli was dramatically affected by several visual variables. Two of these—exposure duration and flicker—are of particular relevance to the present study.

Several tasks revealed a counterintuitive effect of exposure duration: A.H.'s accuracy was much higher for brief than for long stimulus presentations. For example, in pressing a left or right response button to indicate the location of a dot displayed on a computer monitor, her error rate increased steadily with exposure duration, from less than 5% at the briefest exposure (17 ms) to nearly 50% at the longest exposure (1000 ms).

The same phenomenon was observed when

A.H. moved a mouse left or right to indicate the orientation of an arrowhead. When the arrowhead was presented for 50 ms, she made no errors in 48 trials; however, for a 1000-ms exposure her error rate was 46% (22/48).

A.H.'s visual location and orientation perception was also profoundly affected by flicker: She was much more accurate for flickering stimuli than for stimuli of constant brightness. In one experiment A.H. moved a mouse to indicate the location of an X presented for 1000 ms on the left or right side of a computer monitor. In the Steady condition the brightness of the stimulus was constant throughout the display interval, whereas in the Flicker condition the stimulus was turned on and off at 50-ms intervals (i.e., 50 ms on, 50 ms off), causing it to flicker visibly. Whereas A.H. erred on half of the trials in the Steady condition (32/64), she made no errors in the Flicker condition.

Flicker also had a dramatic effect on A.H.'s direct copying (i.e., copying while the stimulus remained in view) of stimulus figures from the Benton Visual Retention Test (Sivan, 1992). Under normal lighting conditions, A.H. made localization and/or orientation errors on 21 of 30 trials (see Fig. 1 for an example). However, when the only illumination in the testing room came from a strobe light flashing at a rate of 25 Hz (thereby producing a strong flicker), A.H. made no errors, copying the stimulus correctly on 20 of 20 trials.

In addition to exposure duration and flicker, several other variables also affected A.H.'s accuracy in perceiving the location and orientation of visual stimuli. For example, her performance was much better for moving than for stationary stimuli (McCloskey et al., 1995). The effects of the visual variables provide further evidence that A.H.'s deficit is visual. Also, the finding that these variables have the same effects on location and orientation perception supports the assumption that A.H.'s location and orientation errors are manifestations of the same underlying deficit.

McCloskey et al. (1995) interpreted the effects of visual variables by proposing that visual processing of spatial location and orientation is carried out in each of two visual subsystems, a transient subsystem specialized for processing rapidly changing (e.g., moving, brief, flickering) visual stimuli, and a sustained subsystem most sensitive to static longer-duration stimuli. In A.H., McCloskey et al. argued, the transient subsystem is intact, whereas the sustained subsystem is impaired, often producing incorrect representations of stimulus location and/or orientation. On this account A.H.'s perception of location and orientation is usually accurate when stimulus conditions favor the (intact) transient subsystem, as with brief, moving, or flickering stimuli. However, when the (impaired) sustained subsystem is strongly activated—as in the case of steady, long-duration, stationary stimuli—localization and orientation errors occur.[3]

The hypothesized distinction between transient and sustained visual subsystems draws upon previous proposals concerning the functional architecture of the visual system (e.g., Breitmeyer & Ganz, 1976; Goodale & Milner, 1992; Lennie, Trevarthen, Van Essen, & Wässle, 1990; Livingstone, 1990; Livingstone & Hubel, 1988; Merigan & Maunsell, 1993; Mishkin, Ungerleider, & Macko, 1983; Ungerleider & Mishkin, 1982), but it differs from

[3] McCloskey et al. (1995) argued that the impairment to A.H.'s sustained subsystem is not one in which visual stimulus information cannot be used to compute location or orientation, and a random choice is made at some level of processing. Instead, A.H.'s errors apparently occur when the sustained subsystem systematically computes an incorrect location or orientation representation from the stimulus, reversing left and right and/or up and down. This interpretation was suggested by several findings. First, A.H. was systematically below chance in some tasks, suggesting systematic miscomputation rather than random choice. (One example is the reaching task described earlier, in which A.H. reached to the wrong side of the table on two-thirds of the trials.) Also, A.H.'s localization errors consistently preserved certain aspects of the stimulus location, indicating that at least some stimulus information was used even when an incorrect location representation was generated. For example, when A.H. erred in the reaching task, she nearly always reached to a location with the correct distance but the wrong direction relative to the midline (e.g., reaching far left for an object on her far right). Also worth mentioning is that A.H. does not report experiencing uncertainty about the location or orientation of objects she is looking at. Rather, she says that she always perceives objects as having specific locations and orientations.

these proposals in some respects. For example, whereas some theorists have proposed a distinction between "what" and "where" subsystems (e.g., Mishkin et al., 1983; Ungerleider & Mishkin, 1982), McCloskey et al. (1995) assumed that both visual subsystems make "where" computations.

Regardless of the merit of the McCloskey et al. (1995) interpretation, the important consideration for present purposes is that the effects of visual variables can be used as tools for probing potential links between A.H.'s visual localization deficit and her reading.

READING AND THE VISUAL LOCALIZATION DEFICIT

What are the implications of A.H.'s visual localization deficit for understanding her reading abilities and disabilities? Conceivably, the visual deficit could affect reading in several ways, at least under ordinary reading conditions. First, A.H.'s visual system might sometimes misrepresent the orientations of letters, leading to confusions among letters differing only in orientation (e.g., *b* and *d*). The individual-word reading task provides suggestive evidence on this point: A.H. made a number of errors that could have resulted from letter orientation confusions (e.g., *bone* → "done"; *rib* → "rip"; *pig* → "dig"; see also the first three examples in Table 1).

Second, A.H.'s visual system might err in representing the relative locations—that is, the ordering—of letters within a word, and in fact her word-reading errors include several that could have resulted wholly or in part from letter-sequence confusions (e.g., *snail* → "nails"; *apple* → "appeal").[4] Third, the visual localization deficit could lead to errors in representing the ordering of words in a sequence, as suggested by A.H.'s frequent word sequence confusions in reading aloud strings of unrelated words.

Although the data from the word and word-sequence reading tasks are suggestive, these data do not constitute strong evidence that A.H.'s visual localization deficit was the cause of her impaired performance on the tasks. For example, we cannot rule out the possibility that errors such as *rib* → "rip" occurred for reasons other than misperception of letter orientation. To explore more systematically the relationship between A.H.'s localization deficit and her reading, we carried out a number of experiments in which she read aloud letters, words, and word sequences. In light of the results we then examined her reading of coherent sentences and paragraphs. Our report on the results of this testing is organized as follows:

Naming Letters
  Experiment 1 Upper vs lower case
  Experiment 2 Brief vs long exposure duration
  Experiment 3 Steady vs flickering displays
Reading Single Words
  Experiment 4 Upper vs lower case
  Experiment 5 Brief vs long exposure duration
  Experiment 6 Steady vs flickering displays
Reading Word Sequences
  Experiment 7 Brief vs long exposure duration
  Experiment 8 Steady vs flickering displays
Reading Paragraphs
  Experiment 9 Normal vs sequence-altered paragraphs
Reading Sentences
  Experiment 10 Acceptable vs unacceptable sentences
  Experiment 11 Low constraint sentences
  Experiment 12 Steady vs flickering displays

Experiments 1–3: Letter Naming

If A.H.'s visual system sometimes misrepresents the orientations of letters, then she should make letter orientation confusions not only in reading words but also in naming individual letters. For a number of lower-case letters, reflecting the letter across a horizontal or vertical axis will yield a visual form corresponding to a

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[4] Many of A.H.'s word-reading errors were neither letter-orientation confusions nor letter-sequence confusions. We offer a possible interpretation for these additional errors in a later section.

different letter. For *b, d, p,* and *q* a left–right reflection, an up–down reflection, or both, will transform one of the letters into another. For example, *b* becomes *d* by left–right reflection, *p* by up–down reflection, and *q* by left–right plus up–down reflection. Also, *n* and *u* are potentially confusable through up–down reflection, as are *m* and *w*. We predicted that A.H. would show impairment in naming these eight *orientation-critical* letters (*b, d, p, q, n, u, m, w*), and specifically that her errors would take the form of letter orientation confusions (e.g., *b* → “d”; *m* → “w”).

For the remaining letters (e.g., *e, k, o*) misrepresenting the letter’s orientation would not necessarily result in a naming error. Some orientation-noncritical letters (e.g., *c, o*) are symmetrical, or nearly so, across horizontal and/or vertical axes; for these letters, at least some reflections would yield a visual representation differing little if at all from the correct representation. Even when a left–right and/or up–down reflection would yield a visual representation substantially different from an accurate representation (e.g., ə), the letter would probably still be identifiable, because regardless of orientation the shape would not be confusable with that of a different letter. Accordingly, we predicted that A.H.’s naming performance would be better for orientation-noncritical letters than for orientation-critical letters.

Experiment 1: Naming Lower- and Upper-Case Letters

In this experiment A.H. named letters presented in lower and upper case. Whereas eight lower-case letters are orientation-critical (*b, d, p, q, n, u, m, w*), only 3 upper-case letters fall into this category. *M* and *W* could be confused with one another through up/down reflection errors (even though these letters have slightly different shapes in most fonts). The only other letter that might be considered orientation-critical in upper case is *P*, for which left–right and/or up–down reflections could lead to confusion with lower-case *b, d,* or *q*. We therefore predicted that A.H.’s performance would be better for upper-case than for lower-case letters, and that her upper-case errors would be restricted largely to *M, W,* and perhaps *P*.

Method. The 26 upper-case and 26 lower-case letters were presented in random order on a computer monitor in blocks of 52 trials. Across two testing sessions, 21 trial blocks were presented. The lower case letters *b, d, p,* and *q* were identical except for orientation, as were *m* and *w,* and *n* and *u.* Upper-case *M* and *W* were non-identical in shape, but an up–down reflection of either letter would yield a form recognizable as the other letter.

Results and discussion. For lower-case letters, A.H. made naming errors on 42 of the 546 trials (7.7%). Her error rate was 23% (39/168) for the orientation-critical letters (*b, d, p, q, n, u, m, w*) but less than 1% (3/378) for orientation-noncritical letters, $t(20) = 7.37$, $p < .001$. All but one of the errors on orientation-critical letters were orientation confusions. For example, across the 21 presentations of *d,* A.H. responded “b” six times, “p” three times, and “q” twice. Similarly, she named *w* as “m” on five trials and *m* as “w” twice. In the one remaining error for an orientation-critical letter A.H. responded to one presentation of *d* by saying that she was not sure. Across the 18 orientation-noncritical letters, A.H. named *v* as “u” once and *z* as “n” twice.[5]

For upper-case letters, most of which are orientation-noncritical, A.H. made only 12 errors in 546 trials (2.2%). This error rate was reliably lower than the 7.7% rate for lower case letters, $t(20) = 5.60$, $p < .001$. Nine of the twelve upper-case errors involved the three orientation-critical letters (*M, W,* and *P*). A.H. named *M* as “w” once, *W* as “m” twice, and *P* as “b,” “d,” or “q” six times.[6] The remaining

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[5] The naming of *z* as “n,” which also occurred for upper-case *Z,* may be related to the fact that a 90° rotation of upper- or lower-case *z* yields a form very similar to upper-case *N.* However, A.H. almost never made 90° rotations for nonverbal stimuli.

[6] Our assumption that the errors for *P* resulted from confusion of upper-case *P* with lower-case *b, d,* or *q* seems plausible in the context of the present experiment, given that each block of trials included both upper- and lower-case letters. However, if upper- and lower-case letters were presented in separate trial blocks, so that *b, d,* and *q* were not possible stimuli in blocks containing upper-case *P,* we

errors were *I* named as “l,” *V* named as “w,” and *Z* named as “n.”

Considering just those letters that are orientation-critical in lower but not upper case (i.e., *b, d, q, n, u*), A.H. made 27 errors on the lower-case forms but no errors on the upper-case forms. This result provides clear evidence that the errors in naming orientation-critical letters arose in processing the visual forms of the letters and not, for example, in retrieving the names of letters that had been identified accurately.

Taken together, the results of this experiment argue strongly that A.H.’s deficit in perceiving the left–right and up–down orientation of visual stimuli affects her perception of letters. First, almost all of her errors occurred for orientation-critical letters. Second, the errors overwhelmingly took the form of orientation confusions (e.g., *d* → “b”; *M* → “w”; *p* → “d”). Finally, performance was dramatically worse for lower-case forms than for upper-case forms of letters that are orientation-critical only in lower case.

Experiment 2: Exposure Duration

In this experiment A.H. named lower-case letters that were flashed for 50 ms (Brief Exposure condition) or remained in view until A.H. made her response (Long Exposure condition). We predicted that as in tasks with nonverbal visual stimuli, A.H.’s performance would be better for brief than for long exposures.

Method. Six blocks of 52 trials were presented. Each block consisted of randomly intermixed brief- and long-exposure trials, with each of the 26 lower-case letters appearing once in the Brief Exposure condition and once in the Long Exposure condition. Stimuli and procedures were otherwise the same as in Experiment 1.

Results and discussion. As predicted, A.H.’s performance was substantially improved by brief exposures. Her error rate was 13% (20/156) in the Long Exposure condition but only 1% (2/156) in the Brief Exposure condition, $t(25) = 2.51$, $p < .05$. In the Long Exposure condition, 19 of A.H.’s 20 errors were orientation confusions (e.g., *q* → “b”; *n* → “u”); the remaining error was *t* named as “j.” In the Brief Exposure condition, A.H.’s only errors were *p* named as “d” and *h* named as “b.”

Experiment 3: Flicker

In this experiment A.H. named lower-case letters presented either continuously (Steady condition) or flickering (Flicker condition). We predicted better performance in the Flicker condition than in the Steady condition.

Method. Two versions of the experiment were run. In the full-alphabet version, three blocks of 52 trials were presented, with each block including one Steady and one Flicker presentation of each of the 26 lower-case letters. In the orientation-critical version only the 8 orientation-critical lower-case letters (*b, d, p, q, n, u, m, w*) were tested. Three blocks of 48 trials were presented, with each block containing three Steady and three Flicker presentations of each letter. In both versions the steady and flickering letters were presented for 1000 ms. The flickering displays—in this experiment and in the other flicker experiments we report—were created by turning the stimulus on and off at 50 ms intervals throughout the display interval.

Results and discussion. In both the full-alphabet and the orientation-critical versions, A.H.’s performance was dramatically better for flickering than for steady letters. In the full-alphabet version she erred on 19% of the trials (15/78) in the Steady condition but made no errors in the Flicker condition, $t(25) = 3.11$, $p < .01$. In the orientation-critical version her error rate was 38% (27/72) in the Steady condition, but only 1% (1/72) in the Flicker condition, $t(8) = 4.48$, $p < .01$. In both versions of the experiment all

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might expect A.H. to name *P* correctly even if it were perceived at an incorrect orientation. This prediction was confirmed in two blocked-presentation experiments involving a total of 16 upper-case and 16 lower-case trial blocks. For lower-case letters, and upper-case *M* and *W*, blocked presentation had no apparent effect on the rate of orientation confusions. However, whereas A.H. erred on 6 of 21 presentations of upper-case *P* under mixed-presentation conditions, she made no errors on *P* over 16 presentations in pure upper-case blocks.

of A.H.'s errors were orientation confusions for orientation-critical letters.

In conjunction with the effects of case and exposure duration, these findings argue strongly that A.H.'s letter-recognition errors stem from the same underlying deficit as her errors in perceiving the location and orientation of nonverbal visual stimuli.

Experiments 4–6: Reading Aloud Individual Words

These experiments explored the effects of letter case, exposure duration, and flicker on A.H.'s reading of individual words.

Experiment 4: Reading Aloud Upper- and Lower-Case Words

A.H. was presented with words for which letter orientation or letter sequence errors could lead to confusion with another word. For example, the orientation-critical word *duck* could be confused with *buck* or *puck* if the orientation of the *d* were misrepresented, and the sequence-critical word *saw* could be confused with *was* if the ordering of letters were misrepresented.

Words were presented in both upper and lower case. For most words we expected case to have little or no effect on A.H.'s performance. However, because some letters are orientation-critical only in lower case, some stimulus words were orientation-critical in lower but not upper case. For example, lower-case *duck* is orientation-critical, but upper-case *DUCK* is not. Whereas the *d* in *duck* might be confused with *b* or *p,* the *D* in *DUCK* should not be confused with any other letter even if its orientation is misperceived. Hence, we expected words that were orientation-critical only in lower case to elicit letter orientation errors with lower-case but not upper-case presentation, leading to higher error rates for the lower-case forms.

Method. The stimuli were 80 words ranging in length from 3 to 12 letters. Forty of the words were orientation-critical in lower case. Of these, 10 were also orientation-critical in upper case (e.g., *WAIL*), and 30 were not (e.g., *DUCK*). Twenty words (e.g., *saw*) were sequence-critical (in both upper and lower case), and the remaining 20 words were fillers (e.g., *curve*). The 80 words were randomly divided into two sets of *40*—sets A and B—with the constraint that half of the words of each type were assigned to each set.

Words were presented in random order on a computer monitor, and they remained in view until A.H. responded. Four blocks of 80 trials were presented over two testing sessions. In Blocks 1 and 4 the set A words were in lower case and the set B words were in upper case; in Blocks 2 and 3 the assignment of word sets to upper and lower case was reversed.

Results and discussion. For lower-case stimuli A.H.'s error rate was 27% (43/160). Letter orientation errors (e.g., *bill* → "pill"; *dean* → "bean"; *wink* → "mink") occurred on 25 of the 80 orientation-critical trials (31%), and one error on a sequence-critical word (*pets* → "debts") apparently involved an orientation confusion. Letter sequence confusions (e.g., *saw* → "was"; *spot* → "pots") were observed on 8 of the 40 sequence-critical trials (20%), as well as on one of the orientation-critical trials (*lips* → "lisp"). A.H. also made 8 additional visually similar word errors on lower-case stimuli (e.g., *thorough* → "through").

For upper-case stimuli A.H.'s error rate was 15% (24/160), reliably lower than the 27% rate for lower-case stimuli, $t(79) = 2.61$, $p < .05$. Letter orientation errors (e.g., *MADE* → "wade") occurred on 4 of the 20 orientation-critical trials (20%), and letter sequence errors (e.g., *BOARD* → "broad"; *SILVER* → "sliver") were observed for 7 of the 40 sequence-critical trials (18%). A.H. also made 13 additional errors (e.g., *PETS* → "pits"), one of which (*FRIEND* → "fired") may have resulted in part from a letter sequence confusion.

For the words that were orientation-critical in lower but not upper case, A.H.'s error rate was 35% (21/60) with lower-case presentation, but only 8% (5/60) with upper-case presentation, $t(29) = 3.40$, $p < .01$. Seventeen of the 21 lower-case errors (81%) were letter orientation confusions. These findings argue strongly that at least some of A.H.'s word-reading errors arose in processing the visual forms of letters, and specifically that some of the errors resulted from misrepresentations of letter orientation. More generally, the results for the orientation-critical items, in conjunction with the finding that A.H. made a substantial number of letter sequence errors (e.g., *saw* → "was"), support the assumption that A.H.'s impairment in reading words aloud is due at least in part to her deficit in visual location and orientation perception.

Experiment 5: Exposure Duration

In this experiment A.H. read aloud lowercase words presented for either 90 ms (Brief Exposure condition) or 1000 ms (Long Exposure condition).

Method. Stimulus lists were constructed from 72 word pairs: 48 orientation-critical pairs (e.g., *mall* and *wall*) and 24 sequence-critical pairs (e.g., *arid* and *raid*). Individual words ranged in length from 3 to 7 letters.

Two blocks of randomly intermixed brief- and long-exposure trials were presented. In the first block one word from each pair was presented in the Brief Exposure condition, and the other word was presented in the Long Exposure condition; in the second block the assignment of words to exposure conditions was reversed. Procedures were otherwise the same as in Experiment 4.

Results and discussion. A.H.'s word reading showed the same effect of exposure duration observed with letters and nonverbal visual stimuli: Her error rate was 24% (34/144) in the Long Exposure condition but only 9% (13/144) in the Brief Exposure condition, χ^2 (1, N = 288) = 11.21, $p < .001$.

In the Long Exposure condition A.H. made 21 letter-orientation errors (e.g., *bell* → "dell"; *mind* → "wind"), 8 letter-sequence errors (e.g., *arm* → "ram"; *raid* → "arid"), and 5 other visually similar word errors (e.g., *cub* → "club"). In the Brief Exposure condition, 5 of A.H.'s 13 errors were letter-orientation confusions, and four were letter-sequence confusions. On three of the remaining four error trials she indicated that the stimulus presentation had been too brief for her to identify the word.

Experiment 6: Flicker

In this experiment A.H. read aloud individual words presented either continuously (Steady condition) or flickering (Flicker condition). Stimuli and procedures were the same as in Experiment 5, except that the Flicker condition replaced the Brief Exposure condition. In both conditions the stimulus words were presented for 1000 ms.

Results and discussion. The effects of flicker were even more dramatic than those of exposure duration: A.H.'s error rate was 23% in the Steady condition (33/144) but only 1% (1/144) in the Flicker condition, χ^2(1, N = 288) = 34.15, $p < .001$. In the Steady condition she made 26 letter-orientation errors (e.g., *wound* → "mound"), 2 letter-sequence errors (e.g., *alter* → "later"), and 5 other errors. The single error in the Flicker condition was a letter-orientation confusion.

Taken together, the effects of case, exposure duration, and flicker provide strong evidence that A.H.'s word reading impairment stems from her visual localization deficit.

Experiments 7–8: Reading Aloud Word Sequences

These experiments explored the effects of exposure duration and flicker on A.H.'s performance in reading aloud sequences of unrelated words. We predicted that brief exposures and flicker would reduce her tendency to produce the words out of order.

Experiment 7: Exposure Duration

In this experiment A.H. read aloud two-word sequences presented in Brief (90 ms) or Long (1500 ms) Exposure conditions.

Method. The 72 stimulus sequences (e.g., *ant hat*) were generated by taking all possible pairs of 9 3-letter words (*ant, egg, fox, hat, key, log, rim, set, van*). (We used short words and short sequences to ensure that the entire sequence could be perceived in a 90-ms exposure.)

Three blocks of 144 trials were presented. In each block the 72 word pairs occurred once in the Brief Exposure condition and once in the Long Exposure condition. Pairs were presented in random order, with brief and long exposure trials intermixed. On each trial the stimulus words were arrayed horizontally, with two character spaces between words.

Results and discussion. In the Long Exposure condition A.H. made word sequence errors (e.g., *fox ant* → *ant fox*) on 55 of the 216 trials (25%). In the Brief Exposure condition, however, she made only 1 sequence error (0.5%), $t(71) = 9.87$, $p < .001$.

In addition to the word sequence confusions, A.H. made 5 other errors. In 4 of these (2 in each condition) A.H. replaced one of the words with another word from the 9-word pool (e.g., *key ant* → "log ant"). In the fifth error, occurring in the Brief Exposure condition, A.H. reported that she had not seen the stimulus sequence.

Experiment 8: Flicker

In this experiment A.H. read aloud five-word sequences presented in Steady and Flicker conditions.

Method. Two hundred 4- to 7-letter nouns were used to construct 40 five-word random sequences (e.g., *earth paint puzzle chemical muscle*). An effort was made to avoid orientation- and sequence-critical words. Words were assigned randomly to sequences and to positions within sequences.

Two blocks of 40 trials were presented, with Flicker and Steady trials randomly intermixed within blocks. In the first block 20 sequences were presented in the Steady condition, and the remaining 20 were presented in the Flicker condition; in the second block the assignment of sequences to conditions was reversed. On each trial the stimulus sequence remained in view until A.H. completed her response.

Results and discussion. In the Steady condition, A.H. made word-sequence errors (e.g., *figure soccer circle knife cactus* → "figure circle knife soccer cactus") on 33 of the 40 trials (84%). In the Flicker condition, however, she made only 1 word-sequence error (3%), $\chi^2(1, N = 80) = 52.4$, $p < .001$.

Experiments 7 and 8 demonstrate that A.H.'s word-sequence reading shows the same effects of exposure duration and flicker observed in visual location and orientation tasks with nonverbal stimuli. These results argue strongly that her word sequence errors, like her letter-naming and word-reading errors, arise from her visual localization deficit.

READING COMPREHENSION AND THE VISUAL LOCALIZATION DEFICIT

The evidence we have presented argues strongly that A.H.'s visual localization deficit affects her reading, at least for individual words and sequences of unrelated words. This evidence raises a question we introduced earlier in the article: How can A.H. achieve apparently normal reading comprehension in her daily life and academic endeavors?

Knowledge-Based Constraints in Reading

In comprehending words, sentences, or text, normal readers rely not only on the visual information extracted from the stimulus itself but also on knowledge of the regularities present at many levels in written language (e.g., Foss, 1982; Morris, 1994; Morris & Folk, 1998; O'Seagdha, 1989, 1997; Potter, Moryadas, Abrams, & Noel, 1993; Potter, Stiefbold, & Moryadas, 1998; Rayner, Pacht, & Duffy, 1994; Sharkey & Sharkey, 1992; Tabossi, 1988; West & Stanovich, 1986; Williams, 1988; Wright & Garrett, 1984). Consider the following sequence of words from a hypothetical sentence: *the horse's hoo_.* Knowledge of English orthography suggests that the missing letter is very unlikely to be a vowel, although it could be any of a number of consonants. Syntactic knowledge indicates that the incomplete word may be a noun, adjective, or adverb; lexical-orthographic knowledge suggests more specifically that the word may be *hoot, hoof,* or *hoop;* and, general world knowledge suggests that *hoof* is the most likely candidate. These and other sorts of knowledge may facilitate comprehension by imposing (typically probabilistic) constraints on the interpretation of information from the stimulus itself. We will refer to these constraints as *knowledge-based constraints.*

Several points of clarification may be in order here. First, we do not intend to suggest that the use of knowledge-based constraints—either by normal readers or by A.H.—is a conscious problem-solving process, or even that the knowledge exploited is necessarily available to awareness. Second, although we draw a distinction between knowledge-based constraints and stimulus information, applying knowledge-based constraints in interpreting some stimulus element (e.g., a word or phrase) often involves the use of information about other elements of the stimulus (e.g., neighboring words or phrases). Third, we use the term *knowledge-based constraints* rather than the seemingly more straightforward *contextual constraints* because some constraints that could conceivably be brought to bear are not contextual in the usual sense of the term (e.g., constraints based on knowledge of simple letter or word frequencies).

In the normal reader, application of knowledge-based constraints may occasionally lead to misrepresentation of stimulus elements that are improbable in context, as when one fails to detect misspellings or syntactic anomalies in proofreading. However, stimulus information is usually weighted heavily enough that accurate internal representations are generated even for low-probability stimuli (e.g., *the horse's hoop*).

For A.H., we suggest, the situation is somewhat different. Because of her visual localization deficit, the stimulus representations generated by her visual system are unreliable: the orientations of letters, the ordering of letters, and the ordering of words are frequently misrepresented (and presumably have been since the time of her first exposure to written language). The situation A.H. faces in reading may therefore be similar to that of a hypothetical normal individual who, from his or her first encounter with written language, was exposed only to error-ridden material such as the following:

> *Stupents exhibiting disruptive pehavior be may evlauated learning fro disaqiliites.*

Under these circumstances A.H.'s reading processes may have developed in such a way as to place less-than-normal weight on visual stimulus information and greater-than-normal weight on knowledge-based constraints. More specifically, we propose that A.H.'s reading mechanisms in essence assume that the material being processed is well-formed and meaningful (even when the representations provided by the visual system indicate otherwise), and further that these mechanisms skillfully exploit constraints at multiple levels (e.g., orthographic, syntactic, semantic) to arrive at a coherent interpretation that is as consistent as possible with the stimulus information. On this account the visual stimulus representations are treated as informative but potentially unreliable clues.

When strong knowledge-based constraints can be brought to bear—as is typically the case with meaningful sentences and text—A.H.'s reading processes may usually be able to recover from the errors introduced by her visual system. (Consider, for example, that the distorted sentence in the above example may be "decoded" without too much effort, yielding *Students exhibiting disruptive behavior may be evaluated for learning disabilities.*) However, when the knowledge-based constraints are weaker—as for words presented out of context or word sequences lacking syntactic structure or semantic coherence—A.H.'s reading processes may be unable to overcome her visual system's errors.

We are not in a position to offer a specific proposal about how A.H.'s reading processes combine stimulus information and knowledge-based constraints in arriving at an interpretation. Nevertheless, the knowledge-based constraints hypothesis offers at least a general account of both A.H.'s apparently normal reading comprehension under high-constraint conditions and her severely impaired performance when the constraints are few and weak. The hypothesis also makes some interesting predictions, which we tested in several experiments. However, before reporting these experiments we briefly discuss A.H.'s errors in reading individual words, suggesting that the knowledge-based constraints hypothesis may explain some aspects of the error pattern that do not follow obviously from A.H.'s visual localization deficit.

A.H.'s Word-Reading Errors

Collapsing over the various tasks in which A.H. read individual lower-case words under ordinary conditions (i.e., long exposures of nonflickering stimuli), she made a total of 238 errors. Ninety-five of these errors (40%) were pure letter-orientation confusions (e.g., *dear* → "bear"), and 22 (9%) were pure letter-sequence confusions (e.g., *mar* → "ram"). One hundred eight of the errors (45%) were other types of visually similar word errors: letter deletions (e.g., *finger* → "finer"), letter insertions (e.g., *nose* → "noise"), and letter substitutions (e.g., *ship* → "snip"). The remaining 32 errors (13%) appeared to involve two or more of the above error types (e.g., *sled* → "sleep"; *shoulder* → "shudder").

The letter-orientation and letter-sequence confusions may be interpreted by assuming that an orientation or sequence error introduced by A.H.'s visual system resulted in a stimulus representation corresponding not to the stimulus word (e.g., *bone*) but instead to a different word (e.g., *done*). However, some aspects of the error pattern cannot be interpreted so straightforwardly. Most notable among these is the finding that all of A.H.'s erroneous responses were words. Clearly, we cannot assume that the errors introduced by her visual system always, or even usually, transformed the stimulus word into another word; presumably, the visual-system errors often resulted in a representation not corresponding exactly to any word (e.g., *finegr* for the stimulus *finger, slep* for *sled, rbother* for *brother*). Why, then, did A.H. never produce nonword responses, or report that a stimulus was a nonpronounceable letter string?

The knowledge-based constraint hypothesis suggests a possible answer: A.H.'s word recognition process implicitly assumes that any letter string encountered in reading is a familiar word, and selects as a match for the stimulus word the most strongly activated entry in the orthographic lexicon, even when this entry does not fully match the stimulus representation. By accepting imperfect matches, the word recognition process would probably often succeed in correctly identifying a stimulus word even if the representation generated by the visual system contained letter-orientation or letter-sequence errors. However, in some instances the erroneous representation of a stimulus word might most closely match the lexical entry for a different word, leading to an error.

This interpretation accounts for the finding that all of A.H.'s errors were words, and may also explain why approximately half of the errors were visually similar word errors other than letter-orientation and letter-sequence confusions (e.g., *finger* → "finer"; *sled* → "sleep"). If, for example, a letter sequence error in the visual processing of *finger* resulted in the stimulus representation *finegr,* the word recognition process might match this representation with the lexical entry for *finer* rather than the entry for *finger;* similarly, the stimulus representation *slep* might activate the lexical entry for *sleep* more strongly than the entry for *sled.*[7]

Tests of the Knowledge-Based Constraint Hypothesis

Experiment 9: Reading Paragraphs

In this experiment A.H. read aloud brief paragraphs adapted from various works of fiction and nonfiction. Paragraphs in the Normal condition were syntactically correct and semantically coherent. However, for paragraphs in the Sequence-Altered condition several syntactic errors were introduced by transposing adjacent words, as in the following example:

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[7] It is certainly possible that factors other than those we have discussed also contributed to the word-reading errors. For example, given that A.H.'s visual deficit was presumably present from the time she was first exposed to written language, her orthographic lexicon may not be entirely normal (although her good word-reading performance with brief or flickering stimuli suggests that she has been able to develop at least reasonably accurate lexical representations). Also, her visual system may have sometimes introduced errors other than letter-orientation and letter-sequence errors (e.g., errors involving misrepresentation of the relative locations of features within a letter). However, in the absence of clear evidence that such factors contributed to her performance, we will focus on the potential effects of letter-orientation, letter-sequence, and (in the case of multiword stimuli) word-sequence errors when interpreting A.H.'s reading impairments.

> The policeman always sat on his horse halfway up the first block from subway the station. For as many mornings as he remember could Arthur had always and stopped given the horse three sugar cubes. The horse had learned to him recognize and always pawed at the curb and stretched out his eagerly neck at Arthur's approach. It was the nicest in thing Arthur's day.

A.H.'s task was to read each paragraph as it was written.

Our principal prediction was that A.H. would frequently restore the transposed words to a syntactically acceptable order when reading the Sequence-Altered paragraphs (e.g., *he remember could* → "he could remember"). The basis for this prediction is straightforward: Unless A.H.'s reading processes can somehow distinguish a word sequence error actually present in a text from a word sequence error introduced by her visual system, the former as well as the latter should frequently be repaired.

Method. Stimuli were 10 Normal and 10 Sequence-Altered paragraphs, each printed on a separate page. The two sets of paragraphs were matched in number of words and number of sentences. Individual paragraphs ranged in length from 61–94 words and included 4–8 sentences. In each of the 10 Sequence-Altered paragraphs 6 pairs of adjacent words were transposed to create syntactically unacceptable word sequences. In all 60 transpositions the two transposed words were in the same sentence, and in 58 of the transpositions the two words appeared on the same line in the printed paragraph.

The 10 Normal paragraphs were presented first, followed by the 10 Sequence-Altered paragraphs. (This presentation order was adopted to exclude the possibility that reading of Normal paragraphs would be influenced by recognition that some paragraphs had errors.) A.H. was instructed to read each paragraph aloud as it was written; no mention was made of errors in the texts. Five control subjects were also tested.

Results and discussion. Considering first the Normal paragraphs, control subjects read these paragraphs at a mean rate of 219 words/min (wpm), with rates for individual subjects ranging from 196 to 232 wpm. Across the 10 paragraphs the control subjects made an average of 11.8 reading errors, including word omissions, word insertions, and misreadings of individual words. The vast majority of these errors did not significantly alter the meaning of the text. The number of errors for individual subjects ranged from 1 to 23.

A.H.'s reading speed for the Normal paragraphs—227 wpm—fell within the control range. However, she made 47 reading errors, four times the control subjects' mean, and over twice the control-subject maximum. A.H.'s errors included 9 word omissions (e.g., *he had played with them and had come to know* → "he had played with them and come to know"), 9 word insertions (e.g., *as if* → "just as if"), and 11 misreadings of individual words (e.g., *sleeping* → "sleepy"). These types of errors occurred at roughly three times the control-subject rate. However, the most striking difference between A.H.'s errors and those of the controls involved word sequence confusions. A.H. made 18 errors of this type, most involving words whose order was not tightly constrained by context (e.g., *speed and determination* → "determination and speed"; *fine, yellowed marble* → "yellowed, fine marble"; *large and dark and cool* → "dark, cool, and large"). Control subjects, in contrast, averaged 1.8 word sequence errors, and none of these subjects made more than 4. A.H.'s errors, like those of the control subjects, in most cases did not substantially alter the meaning of the text. Therefore, her comprehension may well have been good despite her higher-than-normal error rate.

Nevertheless, it seems clear that A.H.'s ability to read material verbatim is not normal, even for connected text. This finding meshes well with the knowledge-based constraint hypothesis. In the case of coherent paragraphs the available constraints may usually be sufficient to allow a reasonably accurate interpretation—in particular, an interpretation that preserves the meaning—to be generated from distorted visual representations. However, a fully accurate verbatim reconstruction may not always be possible (as in the case of underdetermined word orders like *large and dark and cool*).

Turning now to the Sequence-Altered paragraphs, control subjects read these paragraphs at an average speed of 175 wpm, 44 wpm slower than their mean rate of 219 wpm for the Normal paragraphs, $t(4) = 14.83$, $p < .001$. Reading rates for individual subjects ranged from 160 to 191 wpm. A.H. also slowed her reading on the altered paragraphs, but not as much as the control subjects: Her reading rate for Sequence-Altered paragraphs was 205 wpm, only 22 wpm slower than her rate for the Normal paragraphs.

Control subjects read the critical pairs of transposed words (e.g., *him recognize* in *The horse had learned to him recognize*) with a mean accuracy of 72%; that is, on average they read 43.2 of the 60 pairs as written, in the anomalous order. Accuracy for individual subjects ranged from 57 to 88%. For 24% of the critical pairs, the control subjects restored the transposed words to their "proper" order (e.g., *people were who frightened* → "people who were frightened"); we will refer to such errors as *sequence repair errors.* On the remaining 4% of the pairs the controls made some other type of error.

Individual control subjects' rates of repair errors ranged from 8% (5/60) to 37% (22/60). In 31 of the 71 total sequence repair errors, the subject realized the error immediately, and reread the sequence accurately. The mean rate of uncorrected sequence repair errors was 14% (8.2/60), with individual subjects' rates ranging from 0 to 25%.

These results indicate that the control subjects exploited knowledge-based constraints in reading the paragraphs, sometimes to the point of failing to read the material verbatim. Although the subjects eventually detected 86% of the word transpositions, they initially read one-fourth of the transposed pairs in an order that, while highly probable, was not the actual order in the text, and for 14% of the transposed pairs, the controls produced the words in the most probable order without realizing that the actual order was different.

A.H.'s performance on the critical word pairs is presented in Table 3, along with the control-subject means. Remarkably, A.H. read only 3 of the 60 transposed word pairs (5%) accurately. For 51 of the 60 pairs (85%) she made a sequence repair error, and for the remaining 6 pairs (10%) she made some other type of error. In 42 of the 51 sequence repair errors A.H. simply restored the transposed words to their "proper" order (e.g., *favorite their foods* → "their favorite foods"); in the other 9 repair errors she revised the text more extensively. For example, she read *This is why so children many who live in towns are naughty* (with transposed words *children* and *many*) as "That is why children who live in many towns are so naughty." Whereas the control subjects noticed and corrected nearly half of their sequence repair errors, A.H. made no such corrections.

TABLE 3

Performance of A.H. and Control Subjects on Critical Word Transpositions in Experiment 9

	Response distribution on critical word transpositions		
Subjects	Accurate	Sequence repair error	Other error
A.H.	5%	85%	10%
Controls	72%	24%	4%

A.H. was remarkably fluent as she repaired the word transpositions; for only 8 of the 51 sequence repair errors was there any noticeable hesitation or stumbling over words. When asked at the end of the experiment whether she had noticed anything unusual about any of the paragraphs, A.H. said that she had not. (In contrast, all 5 control subjects were very much aware of the word transpositions.)

The results of this experiment strongly support the hypothesis that A.H.'s reading processes, operating under the implicit assumption that the material being read is well-formed and coherent, apply knowledge-based constraints to repair errors introduced by her visual system. The results further suggest that the reading processes have little or no ability to distinguish errors actually present in a text from errors produced by the visual system, and therefore repair the former as well as the latter.

Experiment 10: Sentence Acceptability Judgments

In Experiment 9 A.H. was not informed that the stimulus paragraphs contained errors. However, in Experiment 10 sentences were presented with the explicit instruction that some contained clear grammatical errors. A.H. was told to read each sentence aloud exactly as it was written, and then to indicate whether the sentence was grammatically acceptable. If A.H.'s reading processes operate without her awareness or control to correct errors of the sorts introduced by her visual system, we would expect her to have difficulty detecting such errors even when explicitly instructed to do so.

Three types of sentences were presented. *Acceptable* sentences were syntactically acceptable and semantically coherent (e.g., *The boys were swimming across the lake*). *Unacceptable-Sequence* sentences were syntactically unacceptable due to transposition of two adjacent words or morphemes in an otherwise acceptable sentence (e.g., *My parents are doing they all can to help me*). *Unacceptable-Other* sentences were syntactically unacceptable for other reasons (e.g., *My brother learned to dress herself by the age of three*).

We expected A.H. to perform well on the Acceptable sentences, because errors introduced by her visual system should usually be repaired by her reading processes. For the Unacceptable-Sequence sentences we expected A.H.'s reading processes to repair many of the word sequence errors without her awareness or control, leading her to judge many of the sentences grammatically acceptable. For the Unacceptable-Other sentences our expectations were less clear; because the errors in these sentences were not of the sorts frequently introduced by A.H.'s visual system, we were uncertain to what extent her reading processes would effect repairs.

Method. The stimuli were 20 syntactically and semantically acceptable sentences and 37 syntactically unacceptable sentences ranging in length from 6 to 13 words. The 16 Unacceptable-Sequence sentences were created by transposing two adjacent words (14 sentences) or bound morphemes (2 sentences) of an initially grammatical sentence (e.g., *The dog was when gone we arrived at home; I was surprised by his father's boynessish*). The 21 Unacceptable-Other sentences were generated by introducing other types of syntactic errors, such as violations of number or gender agreement, or inappropriate use of prepositions (e.g., *We ran into several friend at the pool this weekend; I found the book and gave it at him*).

Sentences were presented one at a time on paper. A.H. first read the sentence aloud, and then indicated whether it was acceptable. Instructions stressed that the sentences were to be read exactly as they were written, and that the errors were not subtle flaws such as using *who* instead of *whom.* Five control subjects were also tested.

Results and discussion. For the Acceptable and Unacceptable-Other sentences the control subjects were 99% correct both in reading and judging acceptability. For each of these sentence types, one of the control subjects made a single error. On the Unacceptable-Sequence sentences, control-subject performance ranged from 94% to 100% correct, with a mean of 96%. Two of the control subjects made no errors on the Unacceptable-Sequence sentences; the other 3 controls each made one error in which they repaired the ungrammatical word order in reading a sentence, and then judged the sentence acceptable.

A.H.'s performance on the Acceptable sentences was comparable to that of the control subjects. She made only one minor reading error (*It's a beautiful day, isn't it?* → "It's a beautiful day *today* isn't it?"), and she judged all of the sentences acceptable.

For the Ungrammatical-Sequence sentences, however, A.H. made correct reading responses and acceptability judgments for only 3 of the 16 sentences (19%). For the remaining 13 items (81%) she repaired the ungrammatical word or morpheme order when reading the sentence aloud (e.g., *My parents are doing they all can to help me* → "My parents are doing all they can to help me") and then judged the sentence acceptable. In most instances A.H.'s reading was fluent, and she appeared unaware that she had altered the ordering of words or morphemes. These results provide additional evidence that A.H.'s reading processes operate to repair anomalies in stimulus representations, and that the repairs occur outside of A.H.'s awareness.

On the Unacceptable-Other sentences A.H.'s performance was better, although far below the perfect performance of the control subjects. For 13 of the 21 items in this condition (62%) she read the sentence accurately and judged it unacceptable. For the other 8 sentences (38%) she repaired the syntactic error in her reading response (e.g., *My brother learned to dress herself by the age of three* → "My brother learned to dress himself by the age of three") and judged the sentence acceptable.

The difference in rate of repair errors between Unacceptable-Sequence sentences (81%) and Unacceptable-Other sentences (38%) suggests that A.H.'s reading processes may in some sense be tuned to the types of errors her visual system frequently introduces. In particular, her reading processes may be highly skilled at repairing word sequence errors, with the result that she rarely became aware of these errors when reading the Unacceptable-Sequence sentences. In contrast, the reading mechanisms may be much less adept at repairing infrequently encountered errors such as those in the Unacceptable-Other sentences, with the consequence that these errors were more likely to come to her attention.

In the next experiment we used sentences without errors to test another prediction of the knowledge-based constraint hypothesis.

Experiment 11: Reading and Comprehending Sentences

According to the knowledge-based constraint hypothesis, A.H.'s reading comprehension is good for meaningful material because her reading processes can usually exploit constraints at multiple levels (e.g., orthographic, syntactic, semantic) to repair errors introduced by her visual system. This account predicts that A.H. should show impaired comprehension when the available constraints are insufficient for identifying or repairing visual-system errors that alter the meaning of the stimulus material.

Consider the following sentence: *The Smiths moved from Pittsburgh to Philadelphia.* Syntactic and semantic constraints would probably be sufficient for repairing word sequence errors involving some parts of the sentence (e.g., *The moved Smiths from* . . .). However, in the absence of additional context the available constraints would be inadequate for identifying or repairing at least some sequence errors involving the words *Pittsburgh* and *Philadelphia.* For example, if these words were transposed by A.H.'s visual system (yielding *from Philadelphia to Pittsburgh*) knowledge-based constraints would presumably provide no grounds for determining that an error had occurred, and the sentence would be misinterpreted. For other possible sequence errors (e.g., *from Philadelphia Pittsburgh to*) the available constraints might be consistent with more than one repair (e.g., *from Pittsburgh to Philadelphia* or *from Philadelphia to Pittsburgh*), again creating the possibility of a comprehension error.

Method. Thirty-eight sentences were constructed such that (a) the ordering of two critical words could not be predicted from knowledge-based constraints, and (b) the actual order of the words was crucial for determining the meaning of the sentence. The critical words were separated by one word in 34 sentences, by a bound morpheme in 3 sentences (e.g., *My husband's mother is in town for the game*), and by a comma in 1 sentence (*According to Ed, Bill is coming at 4:00 p.m.*). For each sentence, a question was constructed to probe comprehension of the critical word sequence (e.g., *Where is their new home?* for *The Smiths moved from Pittsburgh to Philadelphia*).

The sentences were presented one at a time on a computer monitor in random order. After A.H. read the sentence aloud, it was replaced on the monitor by a comprehension question, and A.H. gave a spoken response to the question. Five control subjects were also tested.

Results and discussion. The control subjects made no errors in reading critical word sequences. A.H., however, transposed the critical words in 9 of the 38 sentences (24%). For example, she read *The Smiths moved from Pittsburgh to Philadelphia* as "The Smiths moved from Philadelphia to Pittsburgh" and *My husband's mother is in town for the game* as "My mother's husband is in town for the game."

On the comprehension questions the controls ranged in accuracy from 87% to 100%, with a mean of 95%. A.H., however, was correct on only 68% of the questions (26/38). For 25 of the 29 trials in which she read the critical words in the correct order (86%), she answered the comprehension question correctly. However, for 8 of the 9 sentences in which she transposed the critical words her answer to the question was consistent with the erroneous reading response, and therefore incorrect. For example, after reading *At the party Mary gave John a birthday present* as "At the party John gave Mary a birthday present" she responded "Mary" to the question, *Whose birthday was it?* These results confirm the prediction that A.H.'s comprehension would be impaired when knowledge-based constraints were too weak to remedy errors her visual system was likely to introduce.

In addition to transpositions of critical words, A.H. made 10 other errors in reading the sentences. Most of these were misreadings of individual words (e.g., *Bert* → "Bret"), although two were word sequence confusions involving noncritical words (e.g., *The toy car* → "The car toy").

Experiment 12: Flicker

If the word-sequence errors observed in Experiment 11 resulted from A.H.'s visual localization deficit, then flickering presentation of sentences should reduce the error rate. To test this prediction we presented sentences similar to those from Experiment 11 in Steady and Flicker conditions.

Method. The stimuli were 120 sentences in which the ordering of two or more critical words was not predictable from knowledge-based constraints (e.g., *Lucy said Betty was an extraordinary person*). Two blocks of 120 trials were presented, with Steady and Flicker trials randomly intermixed within blocks. In the first block half of the sentences were presented in the Steady condition, and the other half were presented in the Flicker condition; in the second block the assignment of sentences to conditions was reversed.

Results and discussion. Flicker dramatically affected A.H.'s reading performance. The rate of critical word transpositions was 28% (33/120) in the Steady condition but only 2% (2/120) in the Flicker condition, $\chi^2(1, N = 240) = 32.1$, $p < .001$. This result provides strong evidence that the word sequence errors observed in the absence of flicker stemmed from A.H.'s visual localization deficit, and hence that the deficit is implicated in her reading of meaningful material.

GENERAL DISCUSSION

We have analyzed in some detail the reading abilities and disabilities of a university student, A.H. Although A.H.'s academic achievements and self-report suggested normal reading comprehension, she was profoundly impaired in reading aloud isolated words (e.g., *box* → "pox") and sequences of unrelated words (e.g., *shore lemon picnic fabric* → "lemon shore picnic fabric").

Our previous studies with A.H. revealed a remarkable developmental deficit in perceiving the location and orientation of visual stimuli (McCloskey et al., 1995; McCloskey & Rapp, 2000). On the basis of these studies we hypothesized that when reading, A.H. frequently misperceives the orientation and ordering of letters and the ordering of words. These perceptual errors, we suggested, were responsible for her impaired performance in the word and word-sequence reading tasks.

To test this interpretation we carried out eight experiments in which A.H. read aloud letters, words, and word sequences. Experiments 1–3 demonstrated that A.H. was impaired in naming isolated letters and that the vast majority of her errors took the form of letter orientation confusions (e.g., *p* → "b"; *m* → "w"). Experiment 1 also showed that when accurate perception of letter orientation was critical for identifying the lower-case form (e.g., *d*) but not the upper-case form (e.g., *D*) of a letter, A.H.'s performance was much worse for the lower-case form. Experiments 2 and 3 showed further that two visual variables—exposure duration and flicker—

had the same effects in the letter-naming task as in tasks with nonverbal visual stimuli. In particular, A.H.'s letter-naming performance was dramatically better for brief than for long exposures, and for flickering than for continuous displays. Experiments 4–6 demonstrated similar effects of case, exposure duration, and flicker on A.H.'s reading of isolated words, and Experiments 7–8 demonstrated that brief exposure or flicker virtually eliminated A.H.'s word ordering errors in the word-sequence reading task. These results provide compelling evidence that A.H.'s deficit in perceiving the location and orientation of visual stimuli is the underlying cause of her impaired performance on the reading tasks.

We then considered whether this conclusion could be reconciled with A.H.'s seemingly normal reading comprehension in her academic pursuits and daily life. We proposed that A.H.'s reading processes rely heavily on knowledge of regularities at multiple levels in written language to constrain interpretation of the potentially inaccurate stimulus representations generated by her visual system. When the available constraints are strong, as in reading connected text, A.H.'s reading processes may usually be able to "repair" the visual-system errors, resulting in good comprehension. However, when the constraints are weak, as with isolated words or sequences of unrelated words, recovery from visual errors may often not be possible. The use of knowledge-based constraints is not, we argued, a conscious problem-solving process, but rather proceeds without A.H.'s awareness or control.

The knowledge-based constraints hypothesis was tested in Experiments 9–12. Experiments 9 and 10 demonstrated that when A.H. read paragraphs or sentences containing errors of the sorts frequently introduced by her visual system, she spontaneously repaired the errors (e.g., *from subway the station* → "from the subway station"). Further, she was usually unaware of the errors and rarely could detect and report them even when explicitly instructed to do so. These experiments provided evidence that A.H. relies heavily on knowledge-based constraints in reading. Experiment 11 demonstrated that reliance on knowledge-based constraints was in fact necessary for her to achieve adequate comprehension of meaningful material: A.H.'s reading comprehension was found to be impaired for meaningful sentences in which the ordering of two critical words could not be determined from the available constraints (e.g., *Mary* and *John* in *At the party Mary gave John a birthday present*). Finally, Experiment 12 showed that A.H.'s reading errors on sentences of this sort were virtually eliminated with flickering sentence displays, indicating that these errors, like her errors with letters, words, and word sequences, arose from her visual localization deficit.

Implications for the Study of Developmental Cognitive Deficits

The present study provides a strong demonstration that the theoretical and methodological tools of cognitive science can shed light on underlying cognitive dysfunctions in developmental cognitive impairments. The experiments we have reported allowed us not only to characterize A.H.'s reading performance in some detail but also, and more importantly, to link this performance convincingly to a specific deficit of visual perception.

What are the implications of our results for understanding developmental dyslexia? We certainly do not suggest that impaired visual localization is the underlying deficit in all or even many cases of developmental reading disability. However, the results from A.H. do demonstrate that a developmental reading deficit can arise from causes other than those posited by most current theories of developmental dyslexia: The most widely accepted theory (e.g., Bradley & Bryant, 1978, 1983, 1985; Liberman, 1982; Shankweiler & Liberman, 1972) assumes that developmental dyslexia is caused by a phonological deficit, and the principal alternative account (e.g., Galaburda & Livingstone, 1993; Lovegrove, 1993) attributes dyslexia to a dysfunction of the transient visual subsystem (which appears to be intact in A.H.).

Reading is a complex process requiring a multitude of perceptual and cognitive mechanisms, and reading impairments could presumably arise from deficits affecting any of these mechanisms. Indeed, the literature on developmental reading disorders suggests considerable variation in the underlying cognitive dysfunctions (e.g., Ellis, 1985; Martin, 1995). Given these points, the search for a single cause of developmental dyslexia, which characterizes most research in the area, is unlikely to prove fruitful. Furthermore, the probable heterogeneity of the dyslexia category undercuts the rationale for the group-study approach adopted in most developmental dyslexia research. This approach, in which results are averaged over groups of subjects classified as dyslexic, rests on the assumption that the groups (and indeed the population from which they were sampled) are homogeneous at the level of underlying dysfunction.

An alternative approach involves single-case analyses of underlying deficits in many individuals with developmental reading disabilities. This approach, exemplified by the present study (see also Broom & Doctor, 1995; Castles & Coltheart, 1993; Rayner, Murphy, Henderson, & Pollatsek, 1989; Snowling & Hume, 1989; Temple & Marshall, 1983), should provide a basis for characterizing the extent and nature of variation among dyslexics in underlying deficits, and it may also contribute to resolving the apparent contradictions among many of the reported results that are based on group averages.

Achieving an understanding of the potentially diverse underlying dysfunctions is of central importance in developing effective diagnosis and treatment methods for developmental dyslexia (or any other form of developmental cognitive impairment). For example, during her elementary school years A.H. endured several efforts to remediate her severe spelling impairment (which apparently stems, like her reading impairments, from her visual localization deficit). The remediation programs consisted primarily of exercises such as copying words repeatedly or looking up words in a dictionary. Given that these exercises required accurate perception of written words, it is unsurprising that A.H. derived no apparent benefit. Had attempts been made to address her difficulties in reading letters or isolated words, these attempts would surely also have been misdirected. Certainly, no one would have suggested that A.H. read under a strobe light.

Implications for Research on Normal Cognition

Our results also have implications for issues in the study of normal cognition. The effects of flicker and exposure duration on A.H.'s reading provide new evidence concerning the distinction between sustained and transient visual subsystems we drew on the basis of previous findings from A.H. (McCloskey et al., 1995). First, the present results suggest that reading mechanisms have access to information from both the sustained and the transient subsystems. A.H.'s impaired performance with long-duration, continuous presentations of letters, words, and word sequences implies that reading processes receive input from the (impaired) sustained subsystem, whereas her dramatically better performance with brief or flickering displays indicates that the reading processes also receive information from the (intact) transient subsystem.

The present findings also speak to the functions served by the sustained and transient subsystems. McCloskey et al. (1995) argued from A.H.'s performance with nonverbal visual stimuli that both subsystems compute the location of visual stimuli. The results from the word-sequence reading task provide additional support for this conclusion. A.H.'s high rate of word sequence errors with long-duration continuous displays implicates the sustained subsystem in computing the relative locations of words in a string; her virtually error-free performance with brief or flickering displays implies that the transient subsystem also computes relative location.

The results from the letter-naming and word-reading tasks go beyond previous findings to suggest that both sustained and transient pathways contribute not only to localization but also to recognition of visual stimuli. The logic here is the same as for the word-sequence results: A.H.'s frequent misidentification of letters (in isolation or in words) with long, continuous stimulus exposures suggests that the sustained subsystem is implicated in letter recognition, and her vastly improved performance with brief or flickering displays suggests that the transient subsystem also plays a role in the recognition process.

These conclusions raise questions about current conceptions of visual pathways and their functions. Two widely adopted (although by no means universally accepted) assumptions are relevant for our purposes. The first (e.g., Ungerleider & Mishkin, 1982) is that the dorsal visual pathway mediates spatial processing (“where”) whereas the ventral pathway underlies visual object recognition (“what”). The second assumption (e.g., Livingstone & Hubel, 1988; Livingstone, 1990) is that the dorsal stream receives input primarily from an earlier visual pathway (the magnocellular, or M, pathway) that is specialized for low-acuity processing of transient stimuli, whereas the ventral stream’s input comes primarily from a pathway (the parvocellular, or P, pathway) tuned for high-acuity processing of more sustained stimuli.

At least in combination, these assumptions are difficult to reconcile with A.H.’s performance. The present findings, and those from our previous studies of A.H., suggest that both transient and sustained stimuli can drive processing in both “what” tasks (e.g., letter and word identification) and “where” tasks (e.g., localizing an object on a table or words within a sequence). Further, A.H. shows poor performance with sustained stimuli and good performance with transient stimuli in both “what” and “where” tasks, a pattern that is difficult to interpret in terms of pathology affecting a system organized into M/dorsal/“where” and P/ventral/“what” pathways.

These findings might be accommodated by assuming that both M and P pathways provide input to both dorsal/“what” and ventral/“where” streams, or by recasting the functional distinction between the two cortical streams. With respect to the latter option, one might posit that the dorsal and ventral streams are more redundant in their functions than current hypotheses suppose. Another possibility is that the dorsal- and ventral-stream functions, although distinct, are such that cognitive processes typically assumed to require only one or the other processing stream in fact require both. For example, object recognition requires considerable spatial processing (e.g., in representing the spatial arrangement of features in an object). One might therefore consider the possibility that the dorsal and ventral streams interact in recognizing objects, such that the former carries out at least some of the required spatial analysis, whereas the latter supports other aspects of the process (perhaps including aspects that are in some sense spatial). Detailed discussion of these points is beyond the scope of this article; our intent here is merely to suggest directions that could be pursued in future theoretical and empirical work.

Finally, the results from our paragraph- and sentence-reading experiments (including the control subjects’ performance on the sequence-altered paragraphs) add to the available evidence that knowledge-based constraints play a significant role in reading. A.H.’s performance in these experiments, as well as her good reading comprehension in daily life, suggest that these constraints are often quite powerful in meaningful material. Just how powerful the constraints can be, even for sentences in isolation, is illustrated by a task in which A.H. read sentences, some of which included letter orientation, letter sequence, and word sequence errors, as in the following examples:

The young boy took the quppy long on afteruoon walks, often stopping to fetch paly.

The stock market is storngly affected dy dercebtions the the of pulbic.

The agency uses comqueter models and to simluations prebict the effects of human itneraction the with bay.

The computer lab is otfeu durign bnsy the week lats of calsess any in given esmseter.[8]

A.H. was told that some sentences contained

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[8] Prior to introduction of errors, these sentences read as follows: *The young boy took the puppy on long afternoon walks, often stopping to play fetch; The stock market is strongly affected by the perceptions of the public; The agency uses computer models and simulations to predict the effects of human interaction with the bay;* and *The computer lab is often busy during the last week of classes in any given semester.*

errors and that her task was to read the sentences as they were supposed to be; that is, she was instructed to correct the errors while reading. She was also asked to indicate after reading each sentence whether it contained any errors. Her performance was remarkable. Although she stumbled occasionally, she read most of the sentences (including the examples above) very smoothly, repairing the errors without hesitation. Further, for 60% of the sentences with errors (18/30), again including the examples given above, she reported that the sentence was entirely correct.

Although impressive, A.H.'s ability to repair errors can with practice be approximated by normal individuals. Our own experience, and informal experimentation with colleagues, indicates that sentences with multiple errors are quite difficult at first but become much easier after some practice. (Normal individuals continue, however, to be aware that the sentences are full of errors.) These observations suggest that rather minimal stimulus information may often suffice in the reading of meaningful material, and that the use of knowledge-based constraints to minimize stimulus processing may be a significant component of reading skill.

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