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Acquired mirror writing and reading: evidence for reflected graphemic representations

Jay A. Gottfried, Feyza Sancar, Anjan Chatterjee*

Department of Neurology, Center for Cognitive Neuroscience, The Hospital of the University of Pennsylvania, 3 West Gates, 3400 Spruce Street, Philadelphia, PA 19104, USA

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Abstract

Mirror writing occurs when individual letters and whole word strings are produced in reverse direction. By analogy, mirror reading refers to the preference to read mirror reversed over normally written words. These phenomena appear rarely after brain damage and offer insight into the nervous system's organization of visual–spatial and visual–motor representations. We present the case of a 51-year-old patient with persistent mirror writing and reading following traumatic brain injury. She preferred to write in the mirror direction with either hand. She drew asymmetric pictures with the same directional bias as normal right-handed subjects, and she did not exhibit left–right confusion regarding other pictures. By contrast, on picture–word matching and lexical decision tasks, she was faster and more accurate with mirrored than normally written words. This pattern of performance suggests that her behavior was not accounted for by reflected motor programs, or by the mirroring of visual–spatial representations in general. Rather, we suggest that her behavior was produced by privileged access to mirrored graphemes. Furthermore, because she seemed better able to read irregular words in mirrored than in normal formats, we suggest that mirrored representations may exist at the whole word level and not simply at the letter level.

Keywords: Reading; Dysgraphia; Dyslexia; Traumatic brain injury

1. Introduction

Mirror writing is the simultaneous process of reversing individual letters and composing word strings in reverse direction. When held to a mirror, these words can be read normally. Young children, developmental dyslexics, and some healthy left-handed adults may produce mirror text [10,36]. Perhaps the most celebrated mirror writer, Leonardo da Vinci, generated over 5000 notebook pages in reverse [40]. As a parlor trick, it can be induced by asking normal persons to write on the undersurface of a table or on their own forehead [10]. In contrast, pathologically acquired mirror writing is uncommon. Up to 2.4% of patients with right hemiplegia exhibit transient mirror writing [29]. Reported cases usually occur in the setting of stroke, trauma, or toxic-metabolic insults, and almost uniformly involve right-handed individuals forced to use their left hand after right-sided weakness [34,35]. Mirror writing is not studied frequently because it is rare and usually resolves over days to weeks. By analogy, mirror reading consists of the ability to read mirror text. Mirror reading is encountered even less frequently than mirror writing. A few cases of acquired mirror writing are accompanied by mirror reading, and these patients usually have extensive visuospatial deficits and left–right disorientation [18–42].

Mirror writing and reading are associated different brain lesions, including left parietal lobe [22,34], left basal ganglia [7,22], and right supplementary motor area [6], suggesting that a single mechanism does not account for the phenomena. Motor, visuospatial, and visual word-form hypotheses have been advanced to explain these mirror phenomena. The motor hypothesis dates back to Erlenmeyer in 1879 (cited in [10]). This hypothesis proposes that bilateral and reversed (mirrored) motor-writing programs are normally present in opposite hemispheres [6,7,10]. Outward, centrifugal movements are considered most natural and consequently the right hand is predisposed to move from left to right and the left hand from right to left [10,18]. Normally, the dominant (left) motor program guides the right hand in the normal direction, while the non-dominant (right) program is suppressed. However, damage to dominant writing programs releases the contralesional (reversed) program, resulting in mirror writing with the left hand. Motor theories of mirror writing make no predictions about mirror reading, since these motor programs are assumed to be implemented "downstream" of the

* Corresponding author. Tel.: +1-215-662-4265; fax: +1-215-349-5579.
E-mail address: anjan@mail.med.upenn.edu (A. Chatterjee).

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representation of letters and words. In fact, many patients with mirror writing find their own writing difficult to read.

The general visual–spatial hypothesis views mirror words as a specific instance of generally reflected visual–spatial representations, which when pathologically released produce both mirror writing and mirror reading [5,18]. Feinberg and Jones [14] described a striking example of general object reversals in which a left-handed man, after right parietal infarction would light his cigarette at the opposite end, stir his coffee with the spoon handle, and hold the telephone receiver upside-down. Right–left disorientation, hemispatial confusion, and reversals of oculomotor scanning direction may all contribute to the faulty visuospatial processing. Heilman et al. [18] reported such a patient, who reversed directions when indicating how one would run bases on a baseball diamond, and reversed numbers on the picture of an old-fashioned rotary phone dial. Similarly, Lambon-Ralph et al. [22] described a patient with general non-verbal reversals when asked to draw geometric figures and country outlines.

The visual word-form hypothesis was first proposed by Orton [28] in the context of cerebral "dominance." Akin to the motor hypothesis, he suggested that bilateral and reversed graphemes are represented in opposite hemispheres. As children begin learning to read, dual graphemic representations compete for control of lexical processing, leading to frequent reversal errors of both reading and writing. Once hemispheric dominance for language has been established, the dominant visual representation guides lexical routines in the correct orientation, while the non-dominant representation is degraded or suppressed. Injury, or inadequate access, to the normal word form would permit release of the mirrored word forms, leading to mirror reading and writing. Evidence for visual mirror-image reversals has been demonstrated in pigeons [23,24] and optic-chiasm-sectioned monkeys [25,26], and in humans [39]. Corballis and Beale [8] have argued that it does not make sense that each hemisphere would encode mirrored percepts of the same visual stimulus as suggested by Orton. Rather, they propose that each hemisphere harbors mirror memory traces of visual percepts.

We report a patient with acquired mirror reading and writing following a traumatic brain injury in 1992. The chronic and persisting nature of her disorder permitted a study of these phenomena and to test the adequacy of the mirrored motor, general visual–spatial or graphemic representations in accounting for her behavior. We also investigated the level of representation at which these reversed representations might be organized.

2. Case history

The patient, HN, a healthy 51-year-old right-handed [3] woman with a high school education, was involved in a motor vehicle accident in 1992 (at the age of 43). At the scene she was found comatose with right frontal and periorbital lacerations. She regained consciousness in the hospital, but remained disoriented and amnestic for the accident. Cranial CT and brain MRI scans were both normal, and she was diagnosed with traumatic brain injury. Despite significant recovery, she was left with residual cognitive deficits involving mild executive dysfunction, inattention, and anterograde amnesia. However, oral language skills, including naming, repetition, comprehension, and spontaneous speech, were virtually unimpaired. There was no evidence for apraxia, visual agnosia, neglect, or left–right disorientation. The remainder of her neurological exam, including cranial nerves, motor function, reflexes, gait, and station, were normal. A resting brain SPECT scan performed in 1995 revealed bilateral frontal hypoperfusion, in keeping with her dysexecutive syndrome.

The patient's most incapacitating disability was evident in her attempts to read and write. Formerly an avid reader, HN labored for hours over a single magazine article. Writing was equally effortful. However, she came to realize that writing in reverse felt more natural and that these words (and numbers) were easier to read than normal words. HN could not recall any instances of non-lexical reversals with objects or in her activities of daily living. She also denied ever reading or writing in mirror format prior to the brain injury. By her own account, "I write this way so I can read what I wrote." The patient described relying on a "sounding-out" strategy of reading, particularly when words appeared in the normal direction.

Until the time of the accident, HN had been working as a data-entry operator, which demanded facility with reading, writing, and arithmetic. Remarkably, she returned to work after her injury, and was able to perform her job adequately if she pasted rightward-facing arrows at the top left corner of her computer screen. Despite the complexity of her impairments, HN lived independently, managed her finances, raised her children, and even drove a car without effort, joking that the stop signs were all labeled, "POTS." Examples of her handwriting before and after the accident are shown in Fig. 1.

3. Experimental methods and results

Patient HN was tested on several writing, picture drawing, and reading tasks. In some of the reading experiments, her performance was compared to that of three right-handed, age-matched (range, 49–57 years) female subjects. Informed consent was obtained from the patient and from each control subject prior to study. All experiments were conducted in accordance with regulations set forth by the Ethical Committee of the University of Pennsylvania.

3.1. Writing

Studies were undertaken to establish whether HN preferred to write in a mirror fashion with her dominant hand.

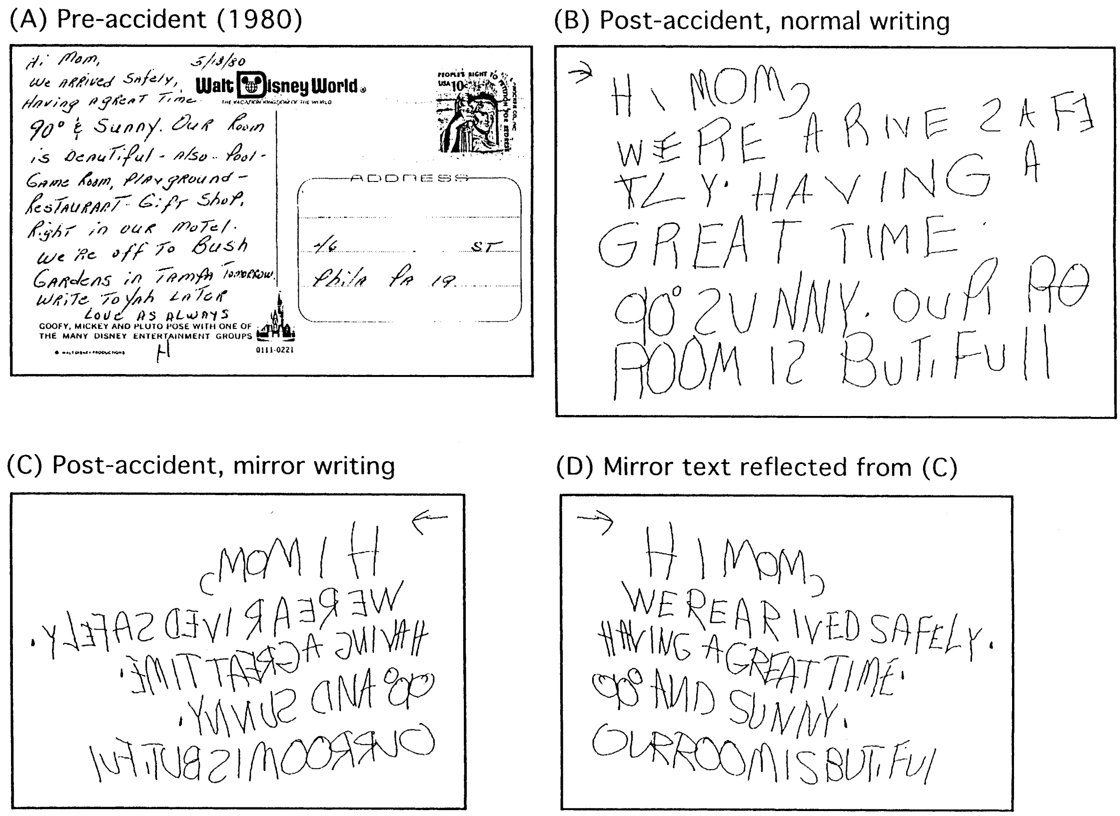

Fig. 1. Handwriting examples before (A) and after (B–D) her brain injury. (A) Normal writing without spelling errors is evident in this postcard the patient wrote to her mother in 1980. (B) She was asked to write the same text to dictation, in the normal direction, which reveals erratic letter construction, occasional letter reversals, and misspelled words. (C) The same text was also written in the mirror direction and is depicted on the same scale as in (B). (D) By reflecting the mirror text in (C) across the vertical axis, it becomes clear that the sizes and shapes of letters and words are formed more neatly and compactly.

According to the motor hypotheses of mirror writing, reversed motor programs within the right hemisphere are thought to guide the left hand in the mirrored direction. This interpretation is borne out by the majority of case reports demonstrating mirror writing confined to the non-dominant (left) hand. Most patients with mirror writing have a right hemiplegia and their writing with the right hand cannot be tested. Since HN did not have right-sided weakness, her writing could be tested specifically with her right hand.

3.1.1. Writing to dictation

HN was asked to write either single words, whole sentences, and numbers to dictation. She was tested using the right and the left hand. HN wrote preferentially with her right hand in the mirror direction (18/18 words), when word direction was not explicitly specified. Number writing was also reversed. These effects persisted whether she wrote on the left or right half of the page. See Fig. 1 for examples of her pre-morbid writing and her writing following her injury. When requested, she was able to write in the normal direction, but found this clumsier, less natural, and more time consuming. Similarly, with her left hand, she also preferred to write in a mirror format (15/16 words), but could produce normal-appearing text with effort.

During sentence composition, the patient had marked difficulty writing letters, words, and numbers in the normal direction (Fig. 2A and B), irrespective of case (upper/lower). The sizes and shapes of letters were erratic, with crowding and overlap of pen strokes. Individual letters and numbers were frequently reversed (29/81 = 36%). She had trouble keeping the words along a steady horizontal axis. It was evident that, despite the instructions to write from left to right, HN overwhelmingly tended to compose each letter from right to left. This resulted in the obvious reversals of asymmetrical letters (e.g. D, K, or S), but even when printing symmetrical letters (e.g. H, T, or W), she adopted a mirrored sequence. For example, when spelling the letter "H" she first drew the rightward vertical line, then the horizontal bar from right to left, and finished with the leftward vertical line. Thus, even though such letters did not appear reversed, their assembly was mirrored. By contrast, when writing in the mirror direction, she printed letters and numbers all in the correct (mirrored in this case) orientation, without reversals (0/77 letters), and word size and shape did not vary with the sentences (Fig. 2C and D). She also wrote more fluidly in this condition, requiring less than half the time to write sentences in mirror than normal direction (approximately 7 s per word versus 19 s per word, respectively).

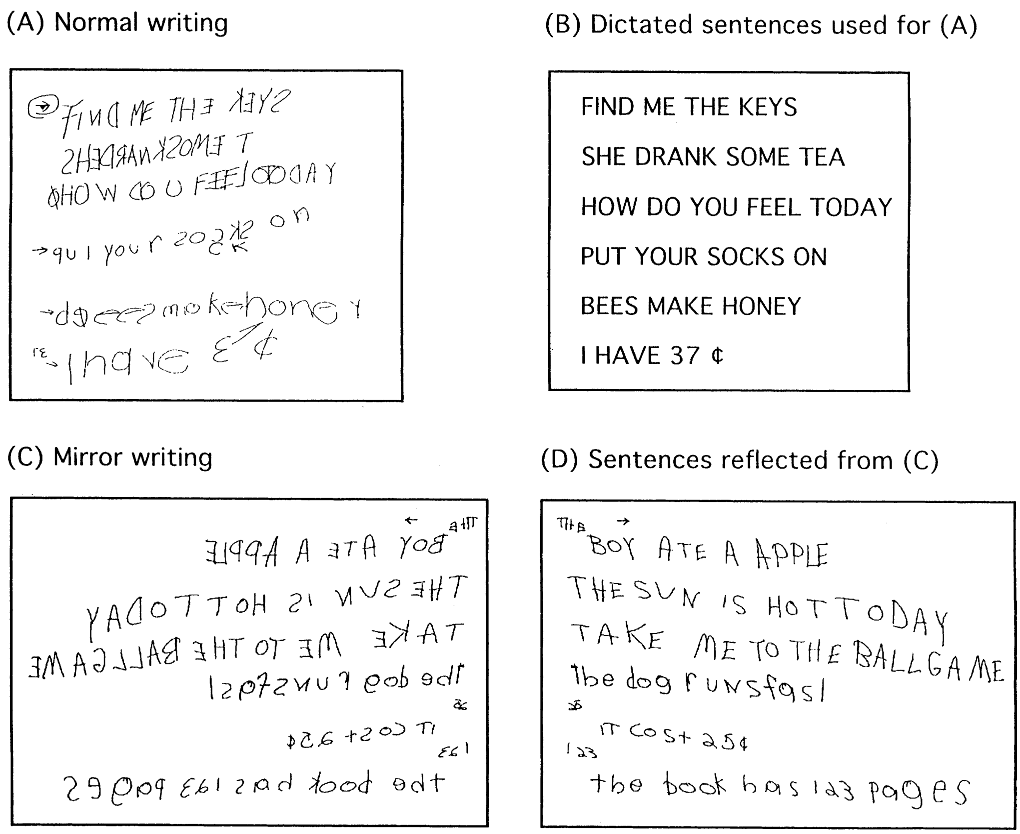

Fig. 2. Sentence writing to dictation: (A) the patient wrote six sentences in the normal direction, exhibiting frequent reversals of individual letters (and numbers), phonetic spelling mistakes, and multiple corrections; (B) the actual sentences used for dictation are displayed beside her attempts; (C) she wrote six different sentences in the mirror direction; (D) horizontal reflection of the mirrored sentences from (C) shows that letters, numbers, and words are formed more naturally, without letter reversals.

3.1.2. Lexical effects

During preliminary writing tasks, HN made numerous spelling errors, particularly of irregular words that cannot be written accurately using spelling-by-sound strategies (such as "BUTIFUL" for "beautiful," Fig. 2). The influence of word direction and regularity on her writing output was examined using 20-word lists of regular, irregular, and non-words, derived from the psycholinguistic assessments of language processing in aphasia (PALPA) [21]. These ranged in length from three to ten words, but were mostly four or five. These words were pseudorandomly assembled into 15-word blocks for oral presentation. Prior to each block, the patient was instructed to write the words to dictation in either the normal or mirror direction. Thus, each word was orally presented twice, comprising 120 stimuli distributed in eight counterbalanced blocks, and she composed each word once in either format, in order to discern whether writing accuracy and speed varied with word direction or regularity.

HN was more accurate when printing regular words in either the normal (17/20) or mirror (20/20) direction, and she was equally successful with non-words (normal, 19/20; mirror, 17/20). In comparison, her performance on the irregular word set was impaired, particularly when instructed to write normally. She was only able to spell half of the irregular words correctly in the normal direction (10/20), and she was somewhat more accurate in the mirror direction (13/20). These data are summarized in Table 1. Again, HN was slower when writing in the normal direction, taking approximately 28 s per word on average, compared to 16 s per word for the mirror condition.

3.1.3. Miscellaneous observations

The patient took longer to compose irregular words and relied heavily on sound-based strategies. She was more successful identifying consonant clusters than vowels and would typically spell an irregular word first by writing down familiar consonants separated by blank placeholders, followed

Table 1
Lexical effects on HNs writing to dictation: accuracy (percentage)

Condition	Normal direction	Mirror direction
Regular words	17/20 (85)	20/20 (100)
Irregular words	10/20 (50)	13/20 (65)
Non-words	19/20 (95)	17/20 (85)

Values given in parenthesis (for normal and mirror direction) are the percentage values.

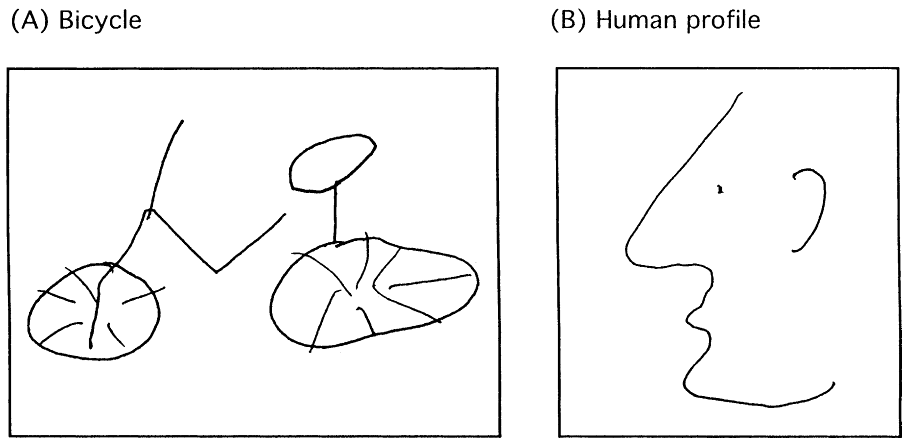

Fig. 3. Spontaneous picture drawing. The patient's freehand depictions of a bicycle (A) and a human profile (B) are both pointing toward the left, representative of a left-directed bias.

by filling-in of the vowels. Thus, in spelling "wind," she began by writing: "W_ND—WIND." She also appeared to more closely approximated the correct spelling of a word when writing in mirror. For example, when asked to spell "giraffe," she produced "GRRF" in the normal direction, but "GIRAFF" in the mirror direction.

3.1.4. Summary

HN preferred to write words in a mirror-reversed fashion with both hands and in both sides of space. She was capable of writing in the normal direction, but found this effortful. When writing normally, she was slower and made more errors, and individual letters were crowded compared to her mirror writing. When writing in a normal direction, asymmetric letters were frequently produced in a mirror fashion. Her propensity to write in a mirrored direction with her right hand is not easily accounted for by the motor hypothesis.

3.2. Drawing

We had HN perform several drawing tasks to test the hypothesis that her mirror behavior was due to a general reversal of visual–spatial representations. These tasks were adapted from directional biases observed in drawings of normal right-handed subjects and tasks of right–left orientation along the lines used by Heilman et al. [18].

3.2.1. Directional bias

Normal right-handed persons have a strong directional bias to draw objects with left–right asymmetries (e.g. airplane, bicycle) pointing to the left [20]. HN was asked to draw one picture: airplane, bicycle, bus, dog walking, door with doorknob, frying pan, handsaw, human profile, tobacco pipe, and water pitcher. If HN drew these objects with the same directional bias as shown in normal right-handers, it would suggest that her mirror writing was not a function of generalized visual reversals, but was specific to lexical or graphemic information. By contrast, directional reversals in her picture drawing (i.e. pointing toward the right) would support a hypothesis involving more generalized mirror reversals of visual–spatial representations.

HN drew all 10 objects pointing towards the left. This directional bias is identical to the bias identified in normal right-handed individuals [20]. Two of her drawings are shown in Fig. 3, revealing the leftward tendency.

3.2.2. Left–right orientation

HN was shown a number of simple pictures that were stripped of their natural left–right informational cues. These included: a baseball field without base names, paired water faucets without hot–cold designations, the front view of an automobile without driver or steering wheel, a traffic intersection without road signs, a bride without a wedding band, and a blank envelope without addresses or postage. The first two of these were derived from Heilman et al. [18]. She was then asked to sketch in the missing information on these pictures, once again to ascertain whether her drawings would reveal generalized visuospatial reversals.

The patient sketched in the missing components of all six picture templates without errors in the left–right axis. When shown the schematic of a baseball field, she correctly labeled the base-running direction (counter-clockwise) and the base positions (first and third), though she mistakenly placed second base at the pitcher's mound (Fig. 4). In contrast, HN persisted in writing the base names ("2" and "3") in mirror format, revealing a dissociation between the graphemic and non-graphemic material. In the remaining pictures, she also assigned all of the elements as is conventional in the United States. These assignments included placing the water-faucet labels (hot on the left), the driver and steering wheel (left side of car), the stop sign (on the right side of a two-lane road), the bride's wedding band (left fourth digit), and the envelope stamp (top right corner) and return address (top left corner).

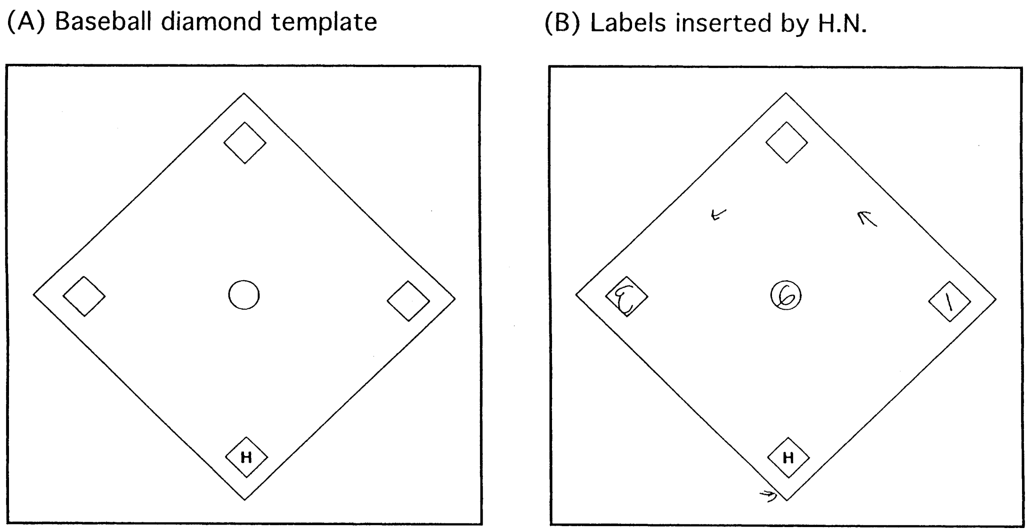

Fig. 4. Visuospatial labeling: (A) the patient was shown a blank template of a baseball diamond with home base (H) specified; (B) base-path direction (counter-clockwise arrows) and base-name locations were correctly indicated, though she accidentally placed the "2" on the pitcher's mound. However, the base numbers themselves ("2" and "3") were still reversed.

3.2.3. Summary

HN drew objects in the same direction as normal right-handed subjects and did not have left–right confusion with pictures. These observations suggest that her mirror writing is not a product of a generalized reversal of visual–spatial representations. As mentioned earlier, remarkably, she was able to drive in city traffic without mishap.

3.3. Reading

Having established that HN did not have a generalized reversal of visual–spatial representations, we investigated her reading abilities in further detail.

3.3.1. Picture–word matching

HN was tested on her ability to match pictures to normal or mirror words. Pictures were composed of 40 black-and-white line drawings of readily identifiable images. These could be described by corresponding three- or four-letter, high-frequency words (e.g. lion, arm, pear). An additional 40 words, matched for frequency and length to the primary word set, were used as non-matching foils. During the experiment, each picture was presented four times, paired once each with: matching word, normal direction; matching word, mirror direction; non-matching word, normal direction; and non-matching word, mirror direction. Thus, there were a total of 160 discrete combinations, one-half of which were correct matches. These picture–word pairs were pseudorandomized and counterbalanced across four 40-word blocks. During each trial, the patient was shown: picture (5000 ms); delay (500 ms); target word, which remained on screen until a push-button response ("Yes": picture–word match). The intertrial interval was 5000 ms. Response accuracy and reaction times (RTs) were recorded. Three age-matched control subjects were tested in order to provide normal response comparisons.

Among a total of 80 responses to picture–word matches, patient HN made eight errors in both the normal and mirror conditions. Thus, of the remaining 64 responses, her RT to normal words was 2565 ± 198 ms, whereas her RT to mirror words was 884±61 ms (Fig. 5A). Of the three control subjects, one made 1 mirror-word error. Out of 232 matching responses, their mean RT to normal words was 568±13.4 ms and to mirror words was 727 ± 30.7 ms.

A related experiment was designed with slight modifications. Here, the words were all presented in the same direction within a given block, and the patient was given an overt directional cue (arrow pasted on the computer screen) at the onset of each block. If a tendency to direct her gaze toward the right played an important role in the patient's mirror reading, then by using the arrow cue to "look left," her performance with normal words would be expected to match that of the mirror words. If, on the other hand, eye gaze were not a determining factor, then the advantage in mirror over normal reading would still be present. Under these simplified conditions, she was still able to perform more accurately and more quickly with mirrored words. Out of 160 picture–word stimuli, she made 10 errors with normal words and 1 error with mirror words. Of the 138 correct responses, she was faster in the mirror direction (2352 ± 102 ms) compared to the normal direction (2655 ± 154 ms).

3.3.2. Lexical decision

A lexical decision task was designed to gather converging evidence in support of the hypothesis that HN had easier access to words in the mirror direction. Stimuli consisted of 240 words corresponding to four categories of 60 words each: real word, normal direction; real word, mirror

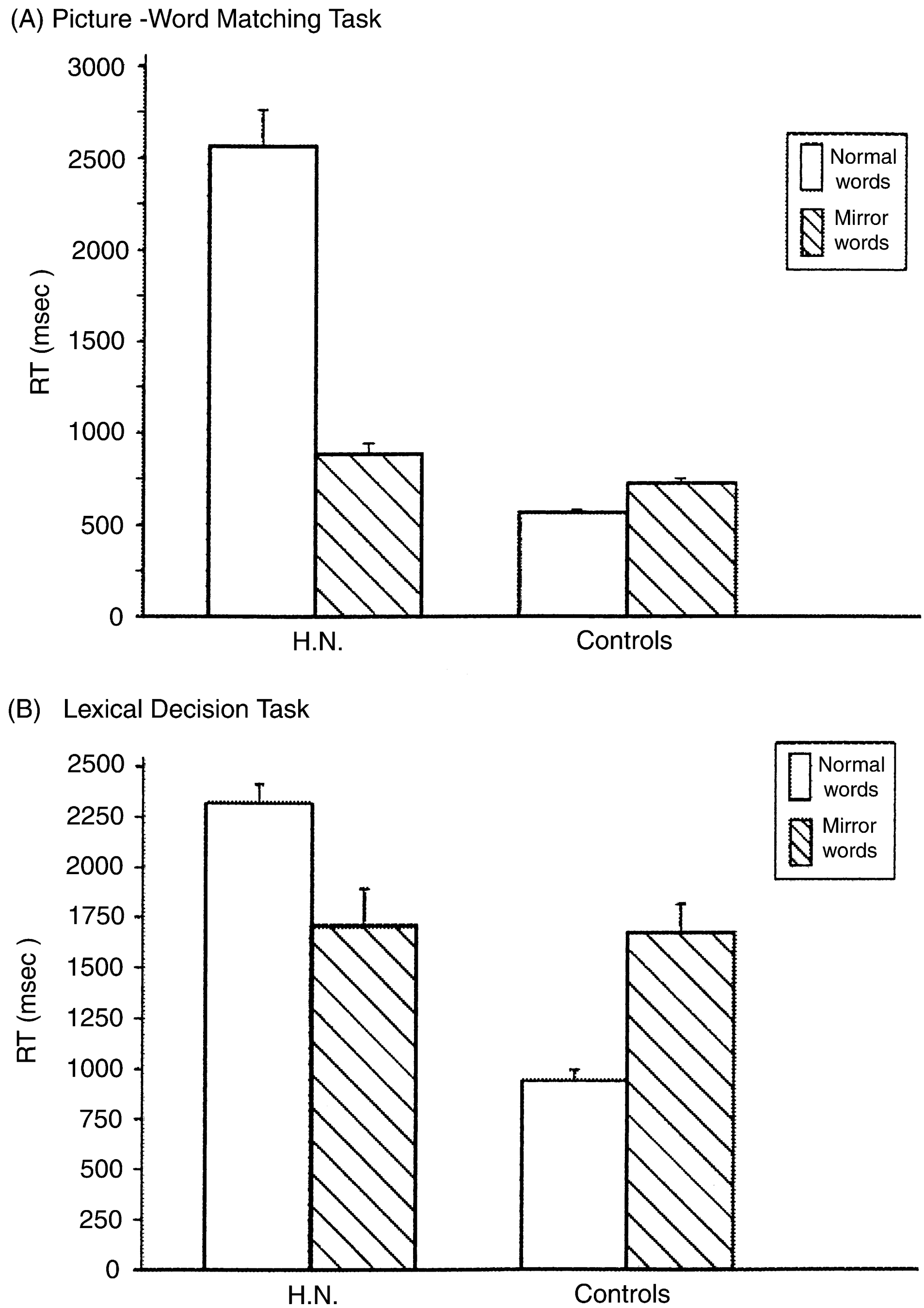

Fig. 5. Reaction times (RTs) in milliseconds of the patient and three age-matched controls, normal vs. mirror reading: (A) picture–word matching task; (B) lexical decision task (regular vs. non-words). Correct mean RTs were taken from the 1000 ms test block.

direction; non-word, normal direction; and non-word, mirror direction. All real words were regular, high frequency, four-letter items with high imageability. Letter strings that spelled out words when read in either direction (e.g. "TRAP"—"PART") were not used. The set of 120 non-words was generated by changing one letter in each of 120 real words. Each non-word could be plausibly pronounced as a single syllable, and care was taken not to formulate any non-words that could be read as real words in the unintended direction (e.g. "PIRD"—"DRIP"). Stimulus delivery was identical to that used in the picture–word task. During each trial, patient HN was shown a fixation cross (5000 ms), followed by the stimulus word in capital letters (variable duration); then a stimulus mask, which remained on screen until a push-button response ("Yes": real word). There were a total of six 40-word blocks, all containing 10 words from each category. In the first block, the stimulus duration was 1000 ms, then shortened by 50–200 ms decrements in successive blocks, until she performed at chance for all word conditions. The patient's accuracy and RT for each block were recorded. The responses of three control subjects were collected under identical test conditions and compared to HNs performance.

An analysis of the RTs, corresponding to all correct responses made during the 1000 ms test block, revealed that HN was faster when reading words in the mirror direction (Fig. 5B). The patient's RT to normal words was 2320 ± 102 ms and to mirror words was 1708 ± 171 ms. The control subjects performed in an opposite manner. Their combined mean RT to normal words was 939 ± 83 ms, in contrast to 1716 ± 601 ms for mirror words. These trends were also observed for the 600 ms test block: HN, 2540 ± 154 ms (normal) versus 1649 ± 134 ms (mirror); controls, 748 ± 365 ms (normal) versus 1287 ± 113 ms (mirror).

At long word-stimulus durations (600–1000 ms), HN made almost no errors when presented with words in either the normal or mirror direction (Fig. 6A). However, as the stimuli exposure became shorter, her performance began to diverge. For the four faster stimulus exposure times she was more accurate with mirror words (59/80) than normal words (40/80; $P < 0.0001$), based on the test of proportion [4].

HNs performance was compared to the mean of three age-matched controls (Fig. 6B). As might be expected, the control subjects made more errors in the mirror condition. Across all stimulus durations, they were less accurate with the mirror words, even at the longest time interval of 1000 ms (normal words, 19.3/20 ± 0.3; mirror words, 16.7/20 ± 0.7). Furthermore, Fig. 6B shows that their

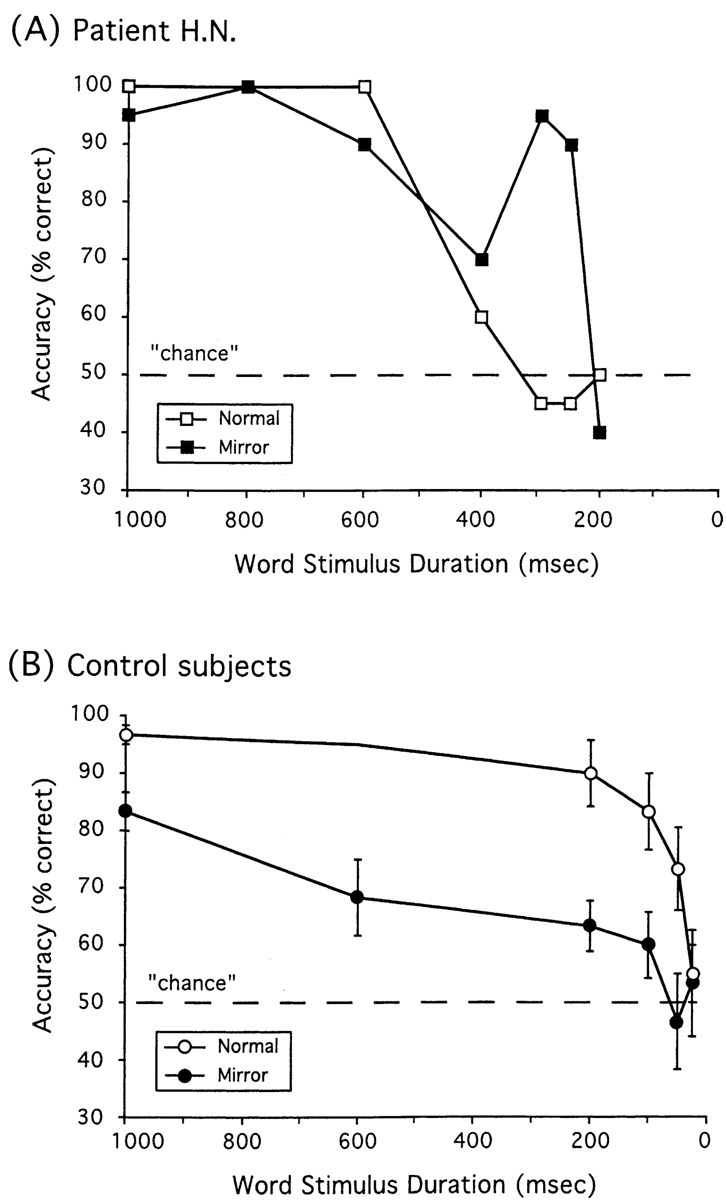

Fig. 6. Response accuracy (percent correct) on the lexical decision task (regular vs. non-words) for both normal and mirror reading, as word duration was progressively shortened: (A) the performance of patient HN; (B) the performance of three control subjects.

performance approached chance sooner with words presented in mirror, as opposed to normal, format.

3.3.3. Reading: regularity effects

Based on HNs writing abilities, we suspected she might have greater difficulty with irregular words (e.g. "island") than regular words (e.g. "inform"). Using word lists from the Battery of Adult Reading Function [17], she correctly read 20/30 (67%) regular words, but only 6/30 (20%) irregular words, when presented in the normal direction. Therefore, a lexical decision task was designed to investigate the effects of word direction and regularity on the patient's reading. The following question motivated this experiment: in addition to privileged access to mirror-reversed graphemes (letters and numbers), did HN have privileged access to mirrored whole word forms? Since irregular words cannot be read using grapheme-to-phoneme correspondence rules, a superior performance for mirrored irregular words would offer at least partial support that the mirrored verbal representations also occurred at the lexical and not simply the sublexical or graphemic level.

Stimuli consisted of 30 regular words and 30 irregular words, matched for frequency and imageability, and 60 non-words, taken from PALPA [21]. These ranged in length from three to ten letters, though most were four or five, and were generally one or two syllables. Each word was presented twice, once each in normal or mirror direction, for a total of 240 items, counterbalanced and assembled pseudo-randomly into six 40-word blocks. Within each block were 10 regular words, 10 irregular words, and 20 non-words, split evenly between normal and mirror direction. For each trial, a fixation cross for 1000 ms was followed by the stimulus word in capital letters, which remained on-screen until a push-button response was made ("Yes": real word).

Out of 30 regular words, patient HN was accurate when items were presented in either the normal (29/30 = 97%) or mirror (29/30 = 97%) direction. She was slightly less accurate with the set of 60 non-words (normal, 55/60 = 92%; mirror, 59/60 = 98%). With irregular words she was less accurate with the normal set (20/30 = 67%) than the mirrored set (26/30 = 87%; $P = 0.02$, test of significance of proportion [4]). These findings are summarized in Table 2.

3.3.4. Miscellaneous observations

During some of the reading experiments, the patient occasionally used environmental cues in the testing room when making her decision. For example, when shown the word, "CEILING," she would briefly direct her gaze up to the actual ceiling, then select the correct response. According to HN, "the word (ceiling) did not look like a real word until after I looked up—then it became a real word." Similar behavior was observed with the words, "DOOR" and "WATCH."

After the lexical decision task involving irregular words was completed, HNs incorrectly rejected words were compiled. Definitions of these words were then given to HN, to assess her knowledge of these words. For example, she was asked, "What is the name for a land mass surrounded completely by water?" or, "Name a high-ranking military class?" In all instances, she was able to provide the correct words (e.g. "island," "colonel"), despite the fact that she was unable to recognize them in their written format.

Table 2
Lexical effects on HNs reading: accuracy (percentage)

Condition	Normal direction	Mirror direction
Regular words	29/30 (96.7)	29/30 (96.7)
Irregular words	20/30 (66.7)	26/30 (86.7)
Non-words	59/60 (91.7)	59/60 (98.3)

Values given in parenthesis (for normal and mirror direction) are the percentage values.

3.3.5. Summary

HN matched words to pictures and made lexical decisions more quickly and accurately when they were written in a mirrored fashion than when they were written normally. This pattern was the opposite of what was observed for age-matched normal subjects. In general, her performance was worse with irregular words than with regular words. However, she performed more accurately with mirrored irregular words than with normal irregular words.

4. Discussion

We present a patient, HN, who had a unique form of acquired mirror writing. She is unusual because, unlike most cases in which left-handed mirror writing is the rule, HN preferred to write mirror words with either hand. This preference persisted for more than 8 years since her initial brain injury, rather than resolving in days or weeks as is more typical. In addition, her mirror writing occurred in combination with a preference for mirror reading. Her pattern of performances on experimental tasks suggests a remarkable modularity of reflected visual forms.

Patient HN preferred to write letters, words, and numbers in the mirror direction with either the right or left hand. She was capable of printing in the normal direction with either hand, but found this more difficult. When she wrote in the normal direction, individual letters were often written in reverse and assembled with strokes from right to left. We think it unlikely that HNs mirror writing is due to released mirror motor engrams. The motor hypothesis postulates that mirrored engrams within the right hemisphere guide the left hand's movement [6,10], but does not predict similar writing with the right hand. Furthermore, one would not expect mirrored motor engrams to be associated with mirror reading as was seen in HN. HNs mirror writing appeared to be a "downstream" effect of mirror-reversed visual–spatial representations.

HNs mirror reading and writing was not due to general reversals of visual–spatial representations. She did not reverse drawings of pictures and was not disoriented with respect to the left and right halves of pictures. Thus, unlike patients reported by Heilman et al. [18] and by Lambon-Ralph et al. [22], on a drawing of a baseball field (Fig. 4), she identified the base paths and base names correctly. Despite this accurate knowledge of the direction that one would run around a baseball diamond, she wrote the numbers on the bases in mirror forms. Similarly, she mirror wrote the letter “C”, despite accurately indicating the sides for “H” and “C” on the hot and cold handles of a paired water faucet. She could identify left–right body parts on herself or an examiner sitting across from her. Finally, unlike the patient reported by Feinberg and Jones [14], she was not compromised in her ability to use physical objects and tools because of confusion about the orientation of objects. Notably, she could drive a car over major interstate routes to the medical center (without getting lost) providing ecological evidence that non-verbal visual–spatial representations that guide navigation were largely preserved.

Across several experiments, it was clear that HN had easier access to mirrored word forms. On the picture–word matching task, unlike normal subjects, her responses were faster to mirror than normal words. On the lexical decision task, also unlike normal subjects, she responded more accurately and quickly to mirror than to normal words. She also needed less time to read mirrored words accurately than normal words.

HNs mirror reading and writing appear to be due to reversals of graphemic representations (letters and numbers). Graphemes are postulated to be stored in reflected forms in opposite hemispheres [28]. Normally, the dominant representation would be expected to guide lexical processing in the normal direction, but in select circumstances, injury or impaired access to this graphemic form would release the non-dominant, mirrored representation, resulting in visual reversals specific to graphemes. These representations would be capable of guiding lexical retrieval (reading) and lexical motor outputs (writing) in a mirrored format.

Two variants on visual–spatial deficits have been proposed to account for mirror writing, neither of which explains HNs behavior. Buxbaum et al. [5] proposed that hemispatial confusion could produce mirror writing. They found that the production of mirror words in right hemispace reverted to normal when written in left hemispace. Hemispatial factors were not evident in our patient. She consistently preferred to write in a mirror format on both halves of the page, and with both hands. Another proposal is that an oculomotor tendency to scan from right to left would favor reading and writing in the mirror direction. This idea was raised in the context of reading reversals seen in developmental dyslexics [15,43] and in acquired adult cases [18,22]. However, the visual scanning hypothesis is unlikely to fully account for HNs behavior. Even when she wrote in the normal direction, she made frequent reversals of individual letters (see Fig. 2A). Importantly, HNs reversals persisted despite the constant directional reminder of a rightward-facing arrow, suggesting that even when the role of visual scanning preferences was offset, the bias toward mirror writing remained. Similarly, on the picture–word matching task, despite overt directional prompts to the left, she was faster and more accurate with mirror than normal words.

While it seemed clear that HN had privileged access to mirror visual letter forms, we tested the hypothesis that she might also have privileged access to mirror forms of whole words. HN was better able to write and read regular and non-words than irregular words. This pattern suggests relatively impaired access to whole word forms, a reading route thought to be used when reading such words [13,37]. By contrast, her ability to read non-words suggests intact grapheme to phoneme conversion mechanisms, and is in accord with her own observations that she needed to “sound out” words when reading. If HN had privileged access to mirrored whole word forms, then her performance on mirrored irregular words might be better than on irregular words written in the normal direction. Consistent with this hypothesis, HN was more accurate on lexical decision tasks when irregular words were presented in mirror than normal formats. These observations are reminiscent of those made by Lambon-Ralph et al. [22], whose patient seemed to read normal words “letter-by-letter” and mirrored words in parallel.

Our case does not offer direct evidence for the neural substrate of mirrored representations. Like many patients with traumatic brain injury, specific damage was not evident on her structural brain imaging. Her SPECT scan showed bilateral prefrontal hypoperfusion, but the relationship of this abnormality to her mirror reading and writing is not obvious. Functional neuroimaging studies appear to implicate the left angular gyrus [19] or left mesial extrastriate cortex [31] in normal visual-word processing. Several patients reported with mirror reading have damage to the posterior occipital–parietal cortex [22,34]. A reasonable candidate for mirrored word representations would be homotopic structures in the right hemisphere linked by commissural pathways [2]. Functional neuroimaging studies of mirror reading activates right hemispheric networks, including parieto-occipital areas adjacent to the right angular gyrus [12,16,32]. Additionally, in a PET study of implicit word processing, Price et al. [33] demonstrated that the usual left-hemisphere activation was accompanied by homologous areas of the right hemisphere.

Why should the nervous system harbor mirror graphemic representations? As Corballis and Beale [8,9] have suggested, organisms need to be able to recognize that the same object can be oriented in different directions. The importance of such “mirror equivalency” means that representations might be encoded in their mirrored forms. Animal studies support the idea of bi-hemispheric encoding and maintenance of mirror visual forms. For example, optic-chiasm-sectioned monkeys monocularly trained to recognize asymmetrical visual objects preferentially respond to the mirror images of these same objects when viewed with the untrained eye [25,26]. The transfer of these representations into their reflected forms may occur in part through the anterior commissure, suggesting that the mirrored forms actually represent memory traces [1] rather than visual percepts, as implied by Orton's original account [28].

Despite the need for mirror equivalency, organisms also need to be able to recognize the specific orientation of objects. A prey unable to determine the orientation of the hunter is unlikely to survive very long. In the macaque, Perrett and colleagues [27,30] have recorded cells within the superior temporal sulcus that are sensitive to specific orientations of certain visual percepts, such as faces and bodies. This ability to appreciate the orientation of objects can be lost following brain damage. Turnbull and McCarthy [41] reported a patient with bi-parietal lesions, who could recognize objects, but could not discriminate between mirror images of these objects. Thus, the advantages of mirror equivalency and the need for orientation specificity pull visual object recognition systems in different directions.

Our case demonstrates that the tension between mirror equivalency and orientation specificity can be restricted to very specific visual forms. Thus, HN was more at ease with mirrored graphemes, but did not exhibit general visual–spatial left–right reversals. It is hard to see how the adaptive advantages of mirror equivalency and orientation specificity apply to written words, although it is germane to one historical form of writing. A bi-directional method of reading and writing known as boustrophedon ("turning like oxen in plowing") emerged in ancient Greece between the eighth and sixth centuries BC. In this writing system the rows of text alternated in the dextrad and sinistrad directions, so that the sentences would successively weave back and forth down the page [40]. Individual letters could be written in either orientation depending on the direction of the writing. Presumably, the nervous system's capacity for mirrored representations was a precondition for the emergence of such a writing system. With the dominance of unidirectional writing conventions, the mirrored representations of visual letters and words no longer seem to have any particular functional significance.

The fact that HN also performed better with mirrored than normally written irregular words suggest that the mirrored representations of graphemes are not restricted to the simple visual forms of individual letters. Thus, the mirrored representations also include complex visual forms, such as irregular words that cannot be recognized by applying grapheme-to-phoneme correspondence rules. In fact, the right hemisphere's general propensity to process visual forms globally rather than locally [11] might even contribute to the relative preservation of irregular word forms in their mirrored representations, if as we suspect the mirrored word forms are stored in her right hemisphere.

In summary, we suggest that mirror reading and writing, which at first glance appear to be a neuropsychological oddity, point to general principles underlying the processing and representation of visual forms. The adaptive advantage of mirror equivalency means that the nervous system harbors visual representations in their normal and reflected forms. The need for orientation specificity means that these different forms must also be distinguishable, and thus can be damaged selectively. These organizational principles that apply to objects in the world generalize to other visual objects, such as letters and words, even though the adaptive advantage for these visual forms no longer applies. Finally, the functional modularity of visual representations themselves means that better access to one kind of mirrored visual form (lexical-graphemes in this case) does not mean that access to all mirrored visual forms is privileged.

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