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Perceptually Based Implicit Learning in Severe Closed-Head Injury Patients

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This study suggests that perceptually based implicit learning may either be preserved following a severe closed-head injury (CHI) or recover within the 1st year. Nineteen severe CHI patients and 19 controls searched visual matrices and indicated the quadrant location of a target. Participants were exposed to the following covariation pattern: AAAABAAA. For Covariation A blocks, the matrices systematically co-occurred with a unique location of the target. This relationship was altered for the B block. Despite CHI participants' overall slower response times (RTs), both groups demonstrated the expected decline in RTs across the first 4 Covariation A blocks followed by an increase when the covariation changed. Both groups also exhibited retention of their learning after a 20-min delay. Explicit knowledge tests indicated that participants lacked awareness for the covariation.

On a daily basis, we are confronted with situations in which our abilities are governed by criteria and rules that can be readily stated. For example, when solving complex mathematical problems, we may rely on our formalized training to guide us through describable steps and rules for answering the problems. Yet not all of our abilities are dependent on our having explicit knowledge for criteria or rules. Consider the example of grammar rules in language. Most people, even from an early age, are able to understand and use complex rules of grammar (e.g., verb tenses) even though they may not be able to describe the rules or how the knowledge was acquired. This is one of many examples that illustrate how important implicit learning processes are in our everyday lives and in the development of our cognitive skills (Cleeremans, Destrebecqz, & Boyer, 1998).

Implicit learning is the term used to refer to the ability to acquire information about the structure or the relationship of objects or events in a complex stimulus environment without an explicit intention of doing so (Berry & Dienes, 1993; Reber, 1993). In contrast to explicit forms of learning that rely on conscious representations of knowledge (e.g., list learning, problem solving, concept learning), implicit learning occurs in the absence of awareness (Graf & Schacter, 1985). Implicit learning processes have been further distinguished from explicit learning processes by their specificity to transfer and their association with incidental versus intentional learning (see Berry & Dienes, 1993). Another distinguishing characteristic between these two learning processes, and the most important one for the purposes of this study, relates to robustness.

Unlike explicit forms of learning, which tend to be adversely affected by attentional demands, as well as time and neurological injury (Reber, Walkenfield, & Hernstadt, 1991), implicit learning processes generally decrease little over a retention interval (Allen & Reber, 1980; Mathews et al., 1989; Nissen, Willingham, & Hartman, 1989) and tend to be unaffected by increases in attentional demands (Cohen, Ivry, & Keele, 1990; Stadler, 1995) or neurological injury. Evidence of preserved implicit learning and impaired explicit processes has been demonstrated in psychotic patients and chronic alcoholics (Abrams & Reber, 1988; Nissen & Bullemer, 1987), Alzheimer's disease patients (Hartman, Knopman, & Nissen, 1989; Nissen & Bullemer, 1987; Nissen et al., 1989), and amnesic and scopolamine-induced amnesic patients (Knowlton, Ramus, & Squire, 1992; Knowlton & Squire, 1994; Nissen, Knopman, & Schacter, 1987). In the present study, we examined implicit learning in patients following a severe closed-head injury (CHI).

Although numerous studies in the CHI literature have investigated explicit learning and memory deficits (for reviews, see Brooks, 1984; Crossen, Novack, Trenerry, & Craig, 1988, 1989; Haut, Petros, Frank, & Lamberty, 1990; Levin & Goldstein, 1986), to date, only a few studies have examined the extent to which the ability to learn and then remember implicit material is intact following a CHI. These previous implicit learning studies have focused primarily on motor sequence learning and have used a serial reaction time (RT) task designed by Nissen and Bullemer (1987). During a typical serial RT task, participants watch for a target to appear in one of generally four locations and then press a corresponding key as fast as possible. The location

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of the target is determined by a specific motor sequence that is repeated across a series of trials; however, the participants are not informed that this is the case. Decreases in RT across patterned blocks and a subsequent increase in RT to a random block are considered to provide a measure of implicit motor learning.

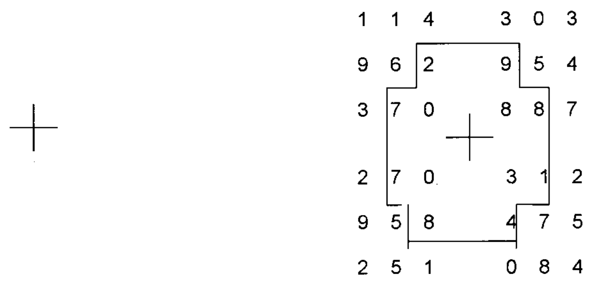
Using the serial RT task, McDowell and Martin (1996) found that patients with CHI and neurologically normal controls both showed improvement across similar patterned blocks and a significant increase in RTs from a patterned block back to a random block, although response times were faster for controls as opposed to patients with CHI. These authors also found that patients with CHI were able to retain the learned pattern across a 20-min activity-filled period. However, because participants' conscious knowledge of the sequence was not assessed in this study, it is difficult to determine whether the improved performance reflected implicit learning, as McDowell and Martin (1996) suggested, or explicit learning. Indeed, Mutter, Howard, and Howard (1994) found a similar pattern of results in a study of mild and moderate to severe head-injured patients. However, both CHI groups in their study demonstrated explicit knowledge for the sequence, suggesting that participants in their study may have benefited from some explicit knowledge of the sequence. Therefore, although participants' implicit knowledge for the motor sequences may have aided their performances, we can't be completely certain that it did.

Although the failure to demonstrate a lack of conscious knowledge makes it impossible to entirely discount the role of explicit processes in the above-cited studies, the finding of improved performance on patterned blocks is typically taken as evidence of implicit learning in the literature. Yet even if we were to assume that the results reflect preserved implicit learning abilities in patients with CHI, this does not necessarily imply that all implicit learning abilities are unaffected by head trauma. Seger (1998) suggested that there are at least three different types of implicit learning—abstract, motor, and perceptual—each of which is proposed to differ in flexibility and automaticity, in the information learned, and in the neural substrates involved (Seger, 1998). In addition to theoretical distinctions, there are methodological distinctions between the different forms of learning that are reflected in the traditional implicit learning research paradigms. For example, tests assessing abstract learning (e.g., artificial grammar studies) evaluate the ability to classify a stimulus. On the other hand, perceptual implicit learning tests measure changes in perceptual processing. Thus, in a perceptual rule task, perceptual aspects of the task establish the rules for target locations (Reed & Johnson, 1998; Stadler, 1989).

To our knowledge, there have been no implicit learning studies in the CHI literature that have used a perceptually based task. To evaluate perceptually based implicit learning following a severe CHI, we adapted a covariation matrix-scanning design from Lewicki (1986a). In covariation learning, individuals are exposed to a simple, nonsalient covariation between stimuli or stimulus features over a large number of trials. Because the covariation pattern is not salient, participants are unable to describe the pattern verbally (Hill, Lewicki, Czyzewska, & Boss, 1989; Lewicki, 1986a, 1986b; Lewicki, Czyzewska, & Hoffman, 1987; Lewicki, Hill, & Bizot, 1988; Lewicki, Hill, & Sasaki, 1989). In the matrix-scanning covariation design used in this study, the participants' task was to detect the location of a target, the number *6*, in a visual display or matrix of digits and to respond by pushing a corresponding button (see Figure 1). Unbeknownst to the participants, the location of the target was determined by an underlying covariation pattern; that is, there was a co-occurring systematic relationship between the location of the target and the arrangement of the other digits presented within the display. This covariation was expected to influence the search for the target by providing information about where to search. Thus, when covariation learning occurs, RTs are faster on covariation blocks compared with altered covariation blocks (Hill et al., 1989; Lewicki, 1986a, 1986b; Lewicki et al., 1989).

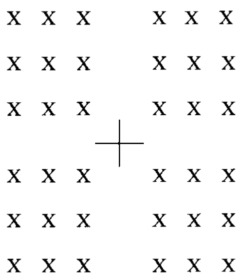
On the basis of previous research, which suggests that neurologically normal controls can use information about the stimulus background to guide their search for target locations despite a lack of awareness for the covariation (Hill et al., 1989; Lewicki, 1986a, 1986b; Lewicki et al., 1989), we formulated several hypotheses. First, because the RTs of CHI participants have been found to be longer on other search–detection tasks (e.g., Schmitter-Edgecombe & Beglinger, 2001), overall response times were expected to be slower for the CHI participants compared with uninjured controls. Second, we expected that if implicit learning skills remain relatively intact following a severe CHI, CHI and control participants would exhibit similar changes in response patterns across a series of learning trials despite differences in their overall reaction times. That is, participants were expected to show a decline in RTs across the first four covariation blocks for the following covariation pattern: AAAABAAA. When Covariation B (in which the target *6* appears in the quadrant diagonally from the one learned in Covariation A) was introduced in the fifth block, RTs were expected to increase. This is because the cues within the visual displays, which previously guided the participants' search for the target *6* in the patterned blocks, would be inconsistent with the location of the target *6* when the Covariation B was introduced, increasing search times. Reaction times were then expected to return to normal when Covariation A was reinstated. Such a disruption in performance would suggest that participants were learning more than the task mechanics (e.g., where to look on the computer screen, how to make key presses). We were also interested in whether the CHI participants and controls would show preserved learning of Covariation A at a 20-min delayed presentation.

To assess participants' access to knowledge about the covariation, we used both implicit and explicit knowledge tests. For the implicit knowledge task, participants were presented with brief exposures of the Covariation A matrices and were asked to indicate the location of the target. This test was completed in spite of the fact that the target *6* did not appear in the visual displays. Implicit knowledge of the Covariation A pattern was considered to be demonstrated if participants were more accurate in deducing the



Fixation cross and auditory tone (500 ms)

Matrix (remains until participant makes a key press)



Mask (500 ms)

Blank screen (500 ms)

Figure 1. Example of the trial sequence for the matrix-scanning task. Participants were to respond by pressing the key that corresponded to the quadrant location of the target *6*. Targets were never placed in positions inside the dotted line (the line did not appear on the matrix display). Errors were followed by a low tone.

location of the target *6* for Covariation A matrices versus novel visual displays. Consistent with a previous study that demonstrated intact perceptually based priming in patients with severe CHI (Schmitter-Edgecombe, 1996), we expected that the performances for both groups on the tachistoscopic identification task would be significantly better for Covariation A than novel visual displays. Because there has been some debate in the literature over how to accurately assess participants' conscious knowledge (see Hendrickx & De Houwer, 1997; Shanks & St. John, 1994), both objective (e.g., forced-choice decision task) and subjective (e.g., semistructured interview) measures were used to assess participants' explicit knowledge for the covariation.

Method

Participants

Nineteen individuals (3 women, 16 men) who had sustained a severe CHI and 19 controls matched for sex, age, and education participated in this study. The majority of the CHI participants were identified through patient records obtained from a regional traumatic brain injury rehabilitation program. The remaining CHI participants were recruited through presentations made at several head injury support groups in the Spokane, Washington area. Control participants were recruited from the community through advertisement. All participants received monetary compensation in return for their time.

Participants were considered to have suffered a severe CHI if review of their medical records indicated that (a) the depth of their coma, as assessed by the Glasgow Coma Scale (Teasdale & Jennett, 1974), was 8 or less ($n = 15$) or (b) the duration of their coma was greater than 24 hr ($n = 1$). In cases where medical records were not available ($n = 1$) or coma depth or duration was not clearly reported in the records ($n = 2$), individuals were considered to have suffered a severe CHI if both the participant and a significant other reported a coma duration of greater than 24 hr (see Richardson, 1990) and a period of posttraumatic amnesia (PTA) that lasted at least 7 days (see Bond, 1983; Richardson, 1990; Russell & Smith, 1961). Careful clinical questioning conducted retrospectively revealed that all of the CHI participants self-reported a coma duration of greater than 24 hr ($M = 26.26$; $SD = 27.59$). Further, 89.5% reported that they remained in a coma for more than 1 week, and 42.1% reported a coma duration of 2 or more weeks. Similarly, all the CHI participants self-reported a PTA duration of 7 days or longer ($M = 51.17$; $SD = 38.63$), with 61.1% of participants reporting PTAs of more than 4 weeks, and 27.8% of more than 9 weeks.

The majority of participants ($n = 15$) suffered their head injury because of a motor vehicle accident; the remainder of the participants ($n = 4$) sustained injuries from a fall of greater than 10 feet. Such high velocity and long acceleration impacts typically result in a large percentage of diffuse axonal injuries (Adams, Graham, Murray, & Scott, 1982). Consistent with the neuropathology of severe CHI (Adams et al., 1982; Adams, Mitchell, Graham, & Doyle, 1977), medical records revealed that the frontal and temporal lobes were the most prevalent sites of contusions, hematomas, and hemorrhages. All CHI participants were assessed at least 1 year following injury ($M = 10.47$; $SD = 7.99$); 84.2% were more than 2 years postinjury, and 63.2% were more than 7 years. CHI participants were also at least 15 years old at the time of injury and less than 55 years of age at the time of testing. Participants were excluded from the study if they had a history of multiple head injuries or other neurological disorders, a history of alcohol or substance abuse, or a history of a significant psychiatric disorder. Because of the visual nature of the stimuli, participants were also excluded if they had less than 20/60 vision or a visual field deficit that would disrupt viewing of a computer screen. Additionally, CHI participants were excluded if they had severe motor deficits (i.e., tremor) in both upper limbs that precluded accurate assessment of reaction times.

There were no differences in the age, $t(36) = -0.01$, or educational level, $t(36) = 0.07$, of the CHI and control participants (see Table 1). Further, there were no group differences in the occupational status of the mothers, $t(33) = 0.62$, or fathers, $t(31) = -1.50$, of the participants (see Table 1). Estimates of premorbid intelligence derived using the Barona formula (Barona, Reynolds, & Chastain, 1984) revealed that the CHI ($M = 105.92$, $SD = 4.40$) and control ($M = 107.53$, $SD = 7.70$) groups did not differ significantly in premorbid abilities, $t(36) = -0.62$. Thus, given these similarities it is likely that the premorbid cognitive skills of the CHI participants did not differ from those of the control participants.

Characteristics of the CHI and control groups are presented in Table 1. The number of participants included in each analysis is also presented, because one control participant did not complete the neuropsychological testing in its entirety, and time constraints precluded some of the CHI participants from completing all measures. These data indicate that the CHI participants were experiencing residual cognitive difficulties. As illustrated in Table 1, *t*-test analyses revealed that the CHI group performed significantly more poorly on tests assessing verbal learning (California Verbal Learning Test; Delis, Kramer, Kaplan, & Ober, 1987), immediate and delayed verbal memory (Wechsler Memory Scale—Revised, WMS–R; Wechsler, 1987), delayed visual memory (WMS–R), category fluency (animal names), and executive functioning (Trail Making Test B; Reitan & Wolfson, 1985). Furthermore, the performances of the CHI group on the immediate and delayed verbal memory tests (WMS–R) fell more that one standard deviation below that of the normative sample. The CHI participants also performed more poorly than the control group on several measures of attention and speeded processing, including the Symbol Digit Modalities Test (Smith, 1991), Trails A (Trail Making Test; Reitan & Wolfson, 1985), and word reading and color naming (Stroop Color Word Test; Golden, 1978). The groups did not differ, however, in overall intellectual abilities as estimated using the Vocabulary, Arithmetic, Similarities, and Block Design subtests from the Wechsler Adult Intelligence Scale—Revised (WAIS–R; Wechsler, 1981). Further, there were no significant group differences on cognitive tests assessing short-term memory span (Digit Span subtest from the WAIS–R) and working memory span (Last Word Sentence Recall; see Daneman & Carpenter, 1980). The lack of differences on these tasks suggests that any differences found

Table 1
Demographic Data and Mean Summary Data for Severe CHI and Control Groups

Variable or test	Mean		Standard deviation		No. of participants		t
	Severe CHI	Control	Severe CHI	Control	Severe CHI	Control	
Age (years)	35.20	35.35	9.26	10.07	19	19	−0.01
Education (years)	14.32	14.26	2.38	2.16	19	19	0.07
Occupation status[a]							
Mother	3.28	2.94	1.97	1.84	18	16	0.62
Father	1.81	2.56	1.05	1.67	16	16	−1.50
CVLT Trials 1–5[b]	51.67	58.89	10.00	6.58	18	18	−2.10*
WMS–R[b]							
Logical Memory I	21.28	32.22	6.96	5.26	18	18	−4.95**
Logical Memory II	16.33	29.67	6.96	6.26	18	18	−5.79**
Visual Reproduction I	35.42	36.78	3.34	3.34	19	18	−1.59
Visual Reproduction II	31.74	35.72	5.19	2.91	19	18	−2.38**
Category fluency[b]	18.44	22.70	4.95	4.54	16	17	−1.96*
SDMT[b]							
Written	50.21	59.22	11.49	9.68	19	18	−2.11*
Oral	55.05	69.00	16.32	11.31	19	18	−2.54**
TMT[b]							
Trails A	31.47	23.83	12.34	4.72	19	18	1.50*
Trails B	74.05	55.50	31.07	12.74	19	18	2.10*
Stroop[b]							
Word	84.00	98.39	7.83	12.25	18	18	−3.81**
Color	63.67	71.78	10.19	6.40	18	18	−2.50**
Interference[c]	51.17	48.33	8.49	5.55	18	18	−1.45
WAIS–R[b] Digit Span	15.67	17.89	3.61	3.98	18	18	−2.11
Reading Span Test[d]	2.74	3.06	0.59	0.94	17	18	1.18

Note. CHI = closed-head injury; CVLT = California Verbal Learning Test; WMS–R = Wechsler Memory Scale—Revised; SDMT = Symbol Digit Modalities Test; TMT = Trail Making Test; Stroop = Stroop Color Word Test; WAIS–R = Wechsler Adult Intelligence Scale—Revised.

[a] Occupational status of each participants' parents was scored on a 6-point Occupational Scale (WAIS–R; 1 = *professional and technical workers*, 6 = *not in the labor force*). [b] Raw scores. [c] Interference = (word × color)/(word + color). [d] Strict span score (Daneman & Carpenter, 1980).

* $p < .05$. ** $p < .01$.

between the groups on the experimental implicit learning and memory tasks cannot be attributed simply to group differences in span capacity.

Stimulus Materials

The stimulus materials in this study were modeled after stimuli used in a matrix-scanning study by Lewicki (1986a). Two sets of four visual matrices, differing only in the arrangement of the digits, were generated for this study. Each matrix contained 36 digits arranged into four quadrants of 9 digits each (see Figure 1). Except for the target *6*, each of the 9 digits was represented four times in each of the four matrices; the target *6* was represented only once per matrix and replaced one of the digits of the matrix. Each trial required participants to move their focus of attention, as the target was always presented outside of the 12 points closest to the fixation point.

For each participant, one set of four matrices was presented during the implicit learning task, and the four matrices in this set subsequently served as the target matrices in the memory tasks that followed. The other set of four matrices was never seen during the implicit learning task and served as novel visual displays for the memory testing. Participants in the CHI and control groups were randomly assigned to one of the two sets of matrices. During the learning trials (Blocks 1–4), the stimuli were arranged so that each of the four matrices systematically co-occurred with a unique quadrant location of the target *6*. For example, whenever Matrix 1 appeared, the target *6* was always located in the upper left quadrant; when Matrix 2 appeared, the target was always located somewhere in the upper right quadrant; and so forth. With the exception of the transfer condition (Block 5), this relationship between the matrix and the location of the target *6* was held constant. During the transfer condition (Block 5), the location of the target *6* was altered so that the *6* appeared in the quadrant diagonal from where it had been displayed during the learning trials. For example, when Matrix 1 was presented during Block 5, the target *6* was located in the lower right quadrant rather than the upper left quadrant.

Apparatus

IBM-compatible personal computers with active matrix screens were programmed with SuperLab Pro Beta Version Experimental Lab Software (1999) to display the stimulus matrices and collect responses and reaction times. At a viewing distance of 30 cm the matrices subtended 13.13° in height and 9.46° in length. All characters presented during the study were 6 mm high and appeared as black on a white background. Each computer was also equipped with a peripheral numeric keypad that participants used to respond. On the keypad, four buttons (*4*, *5*, *1*, and *2*) corresponded to the four quadrants of the matrices. Thus, *4* was labeled *UL*, *5* was identified as *UR*, *1* as *LL*, and *2* as *LR*. Participants were instructed to use the index finger of their dominant hand when responding and to rest their index finger between all four keys between trials.

Procedure

This study involved the following four components: (a) establishment of matrix presentation duration for the implicit knowledge test, (b) implicit learning task and retention phase, (c) implicit knowledge testing, and (d) explicit knowledge testing.

Establishment of matrix presentation duration. Because the CHI participants were expected to exhibit significantly slower speeded processing abilities relative to the controls (see Table 1), tachistoscopic exposure durations for the later implicit knowledge test were individually established for each participant. To determine the matrix exposure durations, we asked participants to identify target locations within visual displays at decreasing presentation rates. Although the positioning of the target conformed to the positioning rules for the experimental testing matrices (as described above), letters (*Z*, *B*, *M*, *H*, *R*, *S*, *G*, *T*, and *J*) replaced numbers in the display to avoid premature exposure to the testing stimuli. Further, the target, which was represented by the letter *O*, randomly appeared in the display and was not determined by the arrangement of the other letters in the matrix. Thus, all the matrices used to obtain the participants' baseline presentation duration for the implicit knowledge test represented a unique arrangement of letters.

After initiating each trial by pressing the space bar, participants were presented with a fixation cross in the center of the computer screen for 500 ms, which was immediately followed by a matrix display. Following the matrix display, a mask of *X*s appeared on the screen for 500 ms followed by a blank screen for 1,000 ms. Participants were asked to verbally identify the quadrant location of the target *O* prior to initiating the next trial. Because the first 10 matrices were used to help participants adjust to the testing procedure, they were presented for a longer duration relative to later trials. All participants were initially exposed to the visual displays for 650.00 ms. The presentation rate was then reduced by 100.02 ms after every two matrices. Following the first 10 matrices, participants were presented with blocks of 10 matrices each. The first trial was presented at a rate of 233.38 ms, and the exposure time was reduced by 16.67 ms after each block of 10 matrices. This continued until the participant's performance was equivalent to chance (30% correct). Thus, the lowest rate at which a participant was able to correctly identify the target location in 3 out of 10 matrices established the presentation rate for that participant on the implicit memory test. For the one CHI participant who scored less than 30% correct at 233.38 ms, the presentation rate was increased to 366.74 ms and then reduced by 16.67 ms after each block until his hit rate again fell to 30%. Additionally, to remain consistent with Lewicki's (1986a) work we established a lower limit of 100.02 ms for participants (CHI, $n = 3$; controls, $n = 11$) who continued to identify more than 30% correct at 100.02 ms.

Implicit learning task. The implicit learning task consisted of three phases: a practice phase, an acquisition phase, and a delayed retention phase.

The beginning of each trial in the practice phase was signaled by a tone presented simultaneously with a fixation cross (500 ms) located in the middle of the screen (see Figure 1). Participants were told to focus on the location of the fixation cross under the guise that it would make their reaction times to the target faster. This fixation cross was immediately followed by the matrix display, which remained on the screen until the participant responded. Twenty-four matrices were presented in the practice phase. For each of the matrices, nine digits were depicted four times within the display. For each trial, the target *6* replaced one of the digits in the display. As noted previously, however, the target *6* never replaced any of the 12 digits immediately adjacent to the fixation cross. After a response was made, a mask of *X*s appeared on the screen for 500 ms, followed by a blank screen for 500 ms. Incorrect responses were signaled by a low tone. This procedure remained consistent for both the practice (24 trials), acquisition, and delayed retention phases.

Aside from the introduction of the covariation sequence, the procedure used for the acquisition phase was identical to that used during practice. During the acquisition phase, participants were presented with the following covariation sequence over eight blocks of 48 trials each: AAAABAAA. For blocks identified as A, the position of the target *6* systematically co-occurred with the placement of the digits in the matrix. For the transfer block, labeled B, the target appeared in the quadrant diagonally opposite from where it was located in the Covariation A learning trials; however, arrangement of the other digits in the matrix remained the same. Consistent with the procedure used in the practice phase, participants were instructed to locate the quadrant location of the target *6*. Additionally, participants were told that their accuracy rates were to remain between 93% and 97% correct. Participants with accuracy rates above 97% at the end of a block were encouraged to respond more quickly to the stimuli. Similarly, participants performing below a 93% accuracy rate were encouraged to respond more carefully on the next 48 trials. With participants operating at the same level of accuracy, any group differences found should be attributable to learning rather than to differences in speed–accuracy trade-off functions (Strayer & Kramaer, 1994). To minimize fatigue and eyestrain, we allowed participant-paced rest breaks between blocks.

The final phase of the task was the delayed retention phase. Following a 20-min delay interval, a block of 48 trials adhering to Covariation A was presented to test the participants' ability to retain the learned pattern. During the delay interval, participants completed several measures that assessed unrelated cognitive skills (e.g., confrontational naming, simple reaction time), as well as a semistructured interview that evaluated their perceptions of their performance across the acquisition phase.

Implicit knowledge testing. For the implicit knowledge task, 48 matrices were presented tachistoscopically to each participant. The four matrices that were presented during the learning trials were each displayed six times and served as the 24 targets. The novel baseline set consisted of the four matrices that were not seen during learning. As with the targets, each of the novel visual displays was presented six times. The target *6* was not displayed in any of the visual displays. Although the target *6* did not appear in the matrices, participants were asked to verbally indicate the quadrant location of the target *6*. Consistent with Lewicki's (1986a) study, participants were encouraged to "relax and let their unconscious take control." Further, participants were encouraged to guess as to the location of the target *6* even if they did not see a *6* in the matrix. For this task, the measure of interest was the number of correct guesses for the location of the nonexistent *6*, particularly in response to the Covariation A matrices (previously presented in the acquisition phase) and the novel visual displays.

The test was self-paced, and each trial was initiated when the participant pressed the space bar. Consistent with the acquisition phase procedures, the order for each trial was as follows: fixation cross, matrix display, mask, and blank screen. The exposure duration for the matrix display, however, differed for each participant. On the basis of the discontinuation criteria described earlier (see *Establishment of matrix exposure duration*), the median presentation rate for the CHI group was 166.67 ms (100.02 ms to 333.40 ms), and the median presentation rate for control participants was 100.02 ms (100.02 ms to 216.71 ms), $t(36) = 3.16$, $p < .005$.

Explicit knowledge tests. Because there has been some debate in the literature over how to accurately assess participants' conscious knowledge (see Hendrickx & De Houwer, 1997; Shanks & St. John, 1994), participants were given two tests of explicit knowledge: an objective criterion measure and a subjective criterion test. For the subjective criterion test, participants were given a semistructured interview, which assessed whether participants could verbally express the systematic relationship in the matrices. Following the interview, participants completed the objective criterion test. At this time, participants were told that a relationship existed between the arrangement of the numbers in the matrix and the location of the target *6*. Both sets of four matrices (Covariation A and novel visual displays) were presented without the target *6*, and each of the eight matrices was presented once. Each matrix remained on the screen until the participant verbally indicated which quadrant he or she believed the *6* should have been located in.

Results

Acquisition Data

Accuracy data. Table 2 displays the average percentage correct as a function of group (CHI or control) and block. A 2 (group) × 8 (block) analysis of variance (ANOVA) on the percentage correct data revealed no significant effects for group, $F(1, 35) = 0.00$, or block, $F(7, 252) = 1.77$. Additionally, the Group × Block interaction was not significant ($F = 0.64$). As can be seen in Table 2, both groups were successful at maintaining their accuracy rate between 93% and 97% across blocks.

RT data. Although planned comparisons were the major mode of analyses, the mean RT data were first analyzed by means of an omnibus 2 (group) × 8 (block) ANOVA with repeated measures on the last factor. The analyses revealed that the overall response rate was slower for the CHI participants ($M = 2{,}326$ ms) compared with the controls ($M = 1{,}684$ ms), $F(1, 36) = 13.26$, $MSE = 294{,}813.83$, $p < .001$. There was also a significant main effect of block, $F(7, 252) = 14.99$, $MSE = 45{,}313.02$, $p < .001$,[1] indicating that response rates changed with practice (see Figure 2). The interaction between group and block was not significant ($F = 1.60$). This suggests that both groups exhibited a similar pattern of performance across the learning trials, despite the CHI group's overall slower response times.

CHI participants. Mean RT data for the CHI group was then independently subjected to a repeated measures ANOVA with block as the repeated factor. As expected, a significant main effect of block was found, $F(7, 126) = 7.46$, $MSE = 65{,}496.22$, $p < .001$. A series of planned comparisons was then completed to examine the pattern of performance across blocks. Specifically, to examine initial learning, we conducted contrasts between Blocks 1 and 4. We contrasted Blocks 4 and 5 to examine the effects of changing the covariation pattern. Finally, we examined participants' recovery following transfer, both immediately and delayed, by comparing Blocks 5 and 6 and Blocks 5 and 8, respectively. As shown in Figure 2, the

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[1] For several of the repeated measures ANOVAs, the assumption of homogeneity of variance was violated. In those cases, we further evaluated the data by adjusting the tests of the significance of the within-subject independent variables using the Greenhouse–Geisser correction and by using a multivariate statistic, Wilks's lambda (Hays, 1988). Because the results from the corrected analyses were identical to the data obtained using the univariate statistic, we have chosen to present the data using the more conventional univariate statistic.

Table 2
Average Percentage Correct for Severe Closed-Head Injury (CHI) and Control Groups on Implicit Learning Task by Block

Block	Mean		Standard deviation	
	Severe CHI	Control	Severe CHI	Control
1	94.74	93.64	0.04	0.04
2	95.83	95.07	0.03	0.02
3	95.18	95.50	0.02	0.03
4	91.89	94.19	0.14	0.04
5 (transfer)	96.16	95.18	0.03	0.03
6	95.50	94.96	0.04	0.03
7	95.60	95.61	0.03	0.03
8	95.26	95.50	0.03	0.02
Delay	94.52	94.63	0.03	0.03

Note. Each accuracy rate data point is based on 48 trials per participant.

mean RT for the CHI group decreased significantly across the first four covariation blocks, $F(1, 18) = 13.58$, $MSE = 167{,}623.21$, $p < .005$. With the introduction of the transfer condition, however, there was a significant increase in the CHI group's mean RT, $F(1, 18) = 5.37$, $MSE = 97{,}973.58$, $p < .05$. The CHI group did not exhibit a statistically significant improvement in their mean RT immediately following transfer (Block 6), $F(1, 18) = 1.41$; however, a significant decrease in mean RT was observed when Block 8 was compared with the transfer condition, $F(1, 18) = 9.64$, $MSE = 74{,}451.86$, $p < .01$. Overall, these results suggest that the CHI participants' performances were being affected by the covariation; the participants' RTs were disrupted by a change in the manipulated pattern and then improved when the initial pattern of covariation was reintroduced over the last three blocks.

Control participants. Consistent with the findings for the CHI group, a main effect of block was found for the control participants, $F(7, 126) = 9.67$, $MSE = 25{,}129.82$, $p < .001$. Similar to the CHI group, planned comparisons revealed that the control group exhibited a decrease in RT between Blocks 1 and 4, $F(1, 18) = 5.16$, $MSE = 68{,}425.38$, $p < .05$, followed by an increase in RT when the transfer was introduced (Block 5), $F(1, 18) = 11.67$, $MSE = 19{,}180.55$, $p < .005$. The controls also exhibited a significant decrease in mean RT between transfer and the final block of trials with the Covariation A pattern (Block 8), $F(1, 18) = 39.99$, $MSE = 32{,}083.34$, $p < .001$. Furthermore, unlike the CHI group, the control participants' performance significantly improved immediately following the transfer with the reinstatement of the initial "learned" covariation pattern (Blocks 5 vs. 6), $F(1, 18) = 12.51$, $MSE = 35{,}316.12$, $p < .005$. Thus, although both groups were affected by the change in the covariation pattern and improved when the initial pattern was reinstated, the CHI group may have needed more time than the control group to recover to pretransfer level following the change in the covariation pattern.

Effect size scores. In comparing group performance changes, we deemed a direct comparison of learning effects inappropriate given the large group differences in overall RTs. Because there is greater variability in slower as opposed to faster RTs, overall slowness tends to inflate RT differences (see Chapman, Chapman, Curran, & Miller, 1994). Subsequently, some studies have attempted to account for overall RT differences using proportional difference scores, where the absolute difference score is divided by a slowness measure. For example, the proportional difference for Blocks 1 and 4 would be represented as (Block 1 − Block 4)/Block 1. Proportional difference scores, however, require that certain unjustified assumptions may need to be made, including that the slowness measure has an intercept of zero and that learning has a similar effect on all the components that contribute to the overall RT (Chapman et al., 1994; Howard & Howard, 1992).

Given the limitations of difference and proportional scores, RTs were not directly compared between the CHI and control groups. Rather, effect sizes were used to describe the amount of learning and disruption that occurred across the covariation blocks for each group (see Table 3). Consistent with the analyses conducted with the RT data, comparisons were made between the following blocks: Blocks 1 and 4, 4 and 5, 5 and 6, and 5 and 8. As can be seen in Table 3, for the control participants, all comparisons between blocks produced large effect sizes. For the CHI participants, with the exception of the small effect size obtained for the comparison assessing immediate recovery (Block 5 to 6), all other comparisons yielded large effect sizes. The finding of a small effect size for the CHI participants in immediate recovery appears consistent with the RT data in suggesting that the CHI group may have needed a longer time to recover from the changed covariation than the control group.

Inspection of the individual participant data revealed, however, that a similar percentage of the CHI and control

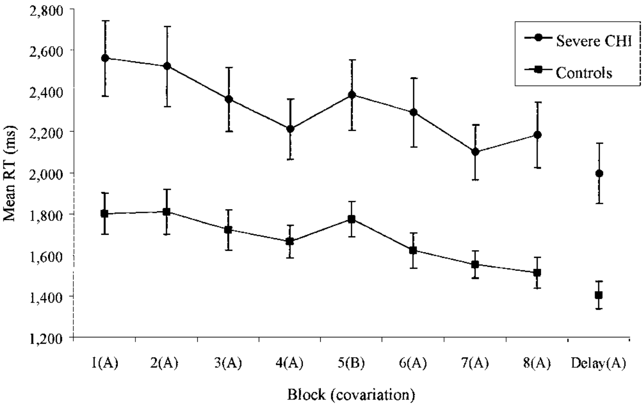

Figure 2. Mean reaction times (RTs) for severe closed-head injury (CHI) and control groups plotted as a function of block. Each block represents a total of 48 trials, with 12 trials per each quadrant. In the fifth block, there was a change in the covariation; for Covariation B, the target appeared in the quadrant diagonally opposite from where it was located in the Covariation A learning trials. The delay block consisted of a block of Covariation A matrices presented after a 20-min delay interval.

Table 3
Effect Size Scores for Blocks of Comparison on the Implicit Learning Task

Blocks compared	Severe CHI	Control
1 vs. 4	.66	.47
4 vs. 5	.48	.63
5 vs. 6	.23	.64
5 vs. 8	.56 (.69)	.83
8 vs. delay	.62 (.39)	.52

Note. Effect size (r) = $[t^2/(t^2 + df)]^{1/2}$, with t representing the t statistic from the mean reaction time comparison between blocks (Rosenthal & Rosnow, 1991). Cohen (1988) suggested the following descriptors for interpreting effect sizes (r): small = .10, medium = .30, and large = .50. Because CHI participants appeared to exhibit fatigue effects in Block 8, some comparisons were made with Block 7 rather than Block 8. These scores are denoted in parentheses. CHI = closed-head injury.

participants (68% and 79%, respectively) achieved a 90% recovery of their initial learning performance (i.e., Block 4 performance) in the block immediately following transfer (i.e., Block 6). Further inspection of the individual data suggested that 5 of the CHI individuals who had difficulty learning the covariation by Block 4 likely drove the appearance of a slower recovery by the CHI participants. These 5 participants exhibited a variable performance in response rate across Blocks 1 through 4 rather than a consistent decrease in RT. They also failed to show the expected interference effect when Covariation B was introduced. It should be noted, however, that 4 control individuals failed to show the interference effect. Given these individual differences, we attempted to determine whether there were any variables that distinguished individuals who exhibited learning of Covariation A by Block 4 from those who did not. We were unable to identify any such variables. That is, participants who were disrupted by the introduction of Covariation B did not differ on any of the neuropsychological, demographic, or injury-related variables from those who showed no interference effect. Furthermore, correlational analyses between a difference measure of the interference effect (Block 4 − Block 5) and the neuropsychological measures (see Table 1) revealed no significant correlations for either the CHI or the control group.

Retention Data

Accuracy data. A t-test analysis revealed that the CHI (M = 94.52%) and control (M = 94.63%) groups did not differ in their mean accuracy rates during the delay condition, $t(36) = -0.11$ (see Table 2).

RT data. To examine whether the participants showed savings for the “learned” covariation over a 20-min delay, we conducted a 2 (group) × 2 (block) ANOVA using mean RT data from Block 8 and the delay. The analyses revealed a significant main effect of group, $F(1, 36) = 14.62$, $MSE = 3{,}766{,}038.98$, $p < .001$, indicating that the CHI participants’ RTs continued to be slower than controls. A main effect for block was also found, $F(1, 36) = 17.60$, $MSE = 414{,}323.77$, $p < .001$. The Block × Group interaction, however, was not significant, $F(1, 36) = 1.25$. These results indicate that not only did both groups show continual savings across the delay but their performance also improved from Block 8 to the delay. Because there was some concern that possible fatigue effects in Block 8 might have exaggerated the amount of savings shown by the CHI group across the delay (see increase in RT from Block 7 to Block 8 for the CHI group in Figure 2), retention data analyses were also conducted using Block 7 performance for the CHI participants rather than Block 8. Even with this more conservative estimate of savings across the delay interval, analyses revealed similar findings; a significant main effect of group, $F(1, 36) = 8.84$, $MSE = 212{,}123.97$, $p = .005$, and block, $F(1, 36) = 14.68$, $MSE = 223{,}498.20$, $p = .001$. There was no Group × Block interaction, $F(1, 36) = 0.01$.

Effect size scores. Effect sizes were also calculated for the retention data in order to account for RT differences between the CHI and control groups. Again, because there was some concern that possible fatigue effects in Block 8 would exaggerate effect sizes for the CHI group, Block 7 was thought to be the better indicator of the CHI participants’ final level of learning performance and was compared against the delay. Block 8 was used in the comparison for the controls. As seen in Table 3, the scores revealed that the CHI and the control groups showed medium and large effect size scores, respectively.

Implicit Knowledge Test

For the implicit knowledge test, we derived a priming effect for each participant by subtracting the proportion of matrices where the quadrant location of the target *6* was correctly guessed given a novel set of visual displays from the proportion of target matrices where the position of the target *6* was correctly deduced given the Covariation A matrices. For the CHI group, the mean proportion correct was .20 (SD = .11) for the novel displays and .24 (SD = .11) for the Covariation A visual displays. The mean proportions correct for the novel and Covariation A matrices for the control group were .26 (SD = .09) and .25 (SD = .08), respectively. Our t-test analyses revealed that neither novel visual display performances, $t(34) = 1.71$, nor Covariation A performances, $t(34) = 1.20$, differed between the groups. Further, neither the CHI group, $t(18) = 1.29$, nor the control group, $t(18) = -0.38$, exhibited a significant priming effect. This suggests that both groups were unable to demonstrate implicit memory for the location of the target within the matrix.

Explicit Knowledge Test

Subjective criterion. When asked to express any observations they made about the visual displays, 57.9% of the CHI participants and 78.9% of the controls denied having any suspicions about the nature of the stimuli. Of those who acknowledged having some suspicions about the stimuli, only one control participant was correct in his or her assumption. Participants were subsequently told that a systematic relationship existed between the location of the target and some cues contained in the displays. When asked to describe what they thought the relationship might be, 63.0% of the CHI participants and 47.4% of the control participants failed to verbalize a relationship. Of those who did provide a response, only one CHI participant was able to correctly identify the relationship. It should be noted, however, that for both participants who verbally expressed some knowledge about the relationship between the target location and the visual display, neither one performed above chance on the objective explicit knowledge measure (see below). Finally, when asked how many different matrices were presented over the learning trials, both groups significantly overestimated the number of matrices. Although participants were actually presented with only 4 matrices, their estimates ranged from 4 to 100 matrices ($M = 22.92$; $SD = 28.44$), with a median response of 8 matrices. Likewise, CHI respondents estimated that there were 5 to 700 matrices ($M = 78.39$; $SD = 172.86$), with a median response of 20 matrices.

Objective criterion. As with the implicit knowledge test data, we derived a difference score for the explicit knowledge test data by subtracting the proportion of matrices where the quadrant location of the target *6* was correctly guessed given a novel set of visual displays from the proportion where the location of the target *6* was correctly deduced given the Covariation A matrices. For the CHI group, the mean proportion correctly guessed was .29 ($SD = .25$) for the novel visual displays and .30 ($SD = .18$) for the Covariation A visual displays. These were not significantly different $t(18) = 0.22$. The means for the control group were .25 ($SD = .25$) and .34 ($SD = .25$) for the novel and Covariation A visual displays, respectively, and were not significantly different $t(18) = 1.00$. Furthermore, comparisons between the groups revealed no significant differences between their guesses given a novel set of stimuli, $t(36) = 0.48$, or between their responses given previously presented matrices, $t(36) = -0.72$.

Discussion

In this study, a matrix-scanning task was used to examine the extent to which the ability to learn and then access perceptually based implicit material is intact in patients with severe CHI. The results revealed that whereas explicit memory abilities (e.g., list learning and prose memory) were impaired in the CHI participants relative to controls, the groups did not differ in perceptually based implicit learning processes. Similar to previous RT and search–detection studies (e.g., Schmitter-Edgecombe & Beglinger, 2001; Schmitter-Edgecombe & Kibby, 1998), the CHI group exhibited overall slower RTs compared with controls. However, despite their slower search rates, the CHI groups' performance across blocks was consistent with that of the control group. For both groups, RTs decreased significantly across the first four covariation blocks. When Covariation B was introduced in the fifth block, RTs were disrupted, suggesting that performance was misguided by the Covariation A that had been acquired in the earlier blocks. Reinstatement of Covariation A in the sixth block subsequently improved RTs for both groups. Overall, the impairment on Block 5 followed by recovery for both groups suggests that participants' improved performances were not solely due to the general learning of task mechanics. Additionally, it appears that learning of the manipulated pattern occurred without participants being aware that they were learning a rule or aware of how the acquired knowledge facilitated their performance, as neither subjective nor objective measures of explicit knowledge revealed evidence of conscious knowledge of the covariation.

Although previous researchers have found dissociations between implicit and explicit memory processes in patients with CHI (e.g., Schmitter-Edgecombe, 1996; Schmitter-Edgecombe & Nissley, 2000), earlier research has failed to convincingly demonstrate intact implicit learning in the absence of conscious awareness (e.g., McDowell & Martin, 1996; Mutter et al., 1994). The current study demonstrates implicit learning in the perceptual domain in patients with CHI without conscious awareness as measured by objective and subjective tests of explicit knowledge. Furthermore, intact perceptually based implicit learning processes were found in this CHI population despite impaired performances on tests of explicit learning and memory. There is a large body of research suggesting that the neural mechanisms that support implicit learning and memory processes may differ from those responsible for explicit processes. Although research on amnesic patients has consistently found that explicit processes are associated with the integrity of the hippocampal formation and diencephalic brain structures (see Hintzman, 1990; Knowlton, Ramus, & Squire, 1992; Weiskrantz, 1987), less is known about the neural structures responsible for implicit functions, perhaps because different neural substrates have been purported to support the different types of implicit learning. Although the basal ganglia and the secondary and primary motor cortex may be important in motor skill learning (e.g., Grafton, Hazeltine, & Ivry, 1995; Pascual-Leone, Grafman, & Hallett, 1994), the association areas of the neocortex are thought to be critical in perceptual learning because of their involvement in the representation of visual stimuli in the perceptual representation system (Gabrieli, Fleischman, Keane, Reminger, & Morrell, 1995; Goshen-Gottstein & Moscovitch, 1995; Seger, 1994; see Tulving & Schacter, 1990). Subsequently, whereas the current study along with previous findings suggests that implicit learning in both perceptual and motor domains may be intact in patients with severe CHI at least 1 year postinjury, it is unlikely that both types of implicit learning would be supported in other neurological populations, for example Parkinson's disease, because of the differences in the neural substrates for the different types of implicit learning.

Similar to previous studies that have found savings for implicitly presented material in neurologically impaired patients (Knopman, 1991; McDowell & Martin, 1996; Mutter et al., 1994; Nissen et al., 1987, 1989), we found that implicitly learned information can be retained and, perhaps, used over a delay to improve performance. The continued improvement in performance that we found across the 20-min delay indicates that asymptotic performance had not been reached during learning. Thus, it is likely that performances would have continued to improve had additional trials of Covariation A been administered during learning. In fact, those participants who failed to exhibit learning of Covariation A following administration of Blocks 1 through 4 appeared to exhibit some learning of Covariation A by completion of Block 8. This suggests that there were individual differences in the rate at which participants acquired Covariation A. We were, however, unable to find any neurologic, demographic, or injury-related variables that distinguished participants who had acquired Covarition A by Block 4 (i.e., they were disrupted by the introduction of Covariation B) from those who had not. It is also possible that the continued improvement evident across the 20-min delay could have been partly related to fatigue. That is, participants may have profited from the 20-min rest break.

Despite evidence of implicit covariation learning from the matrix-scanning task, the present study failed to demonstrate priming effects on the implicit knowledge task. The fact that both the CHI and control participants exhibited chance performance on the implicit knowledge test suggests that the noted performance changes may have been related to something other than (or in addition to) the perceptual aspects of the visual displays. Clearly, the improved performance across the covariation blocks, including the delay, suggests that participants retained some memory for the learned covariation. It may be that participants encoded the covariation but were unable to later activate the trace sufficiently because our implicit knowledge test lacked sensitivity, perhaps because the target location cues contained within the matrices were shown too quickly. In other words, the ability to detect the covariation with our implicit knowledge test may have been compromised if critical perceptual cues within the visual displays were missing or not detected (Shanks & St. John, 1994), because the exposures were too fast to fully activate them. Matrices in the implicit knowledge task could, therefore, have been seen as ambiguous and unrelated to the previously presented material.

Alternatively, participants may have learned something other than the expected covariation in the learning trials. Participants could have learned another feature of the matrices that was unrelated to the covariation manipulation, which could also possibly account for some of the individual differences noted in the participants' ability to learn the covariation. Consequently, the implicit knowledge task may have been an insufficient measure of what participants actually knew because it was assessing something different from what was learned (Shanks & St. John, 1994). Although it seems that perceptual processing is an important component of the matrix-scanning task, it is also possible that other mechanisms played a role (e.g., motor aspects associated with eye movements to target locations). Different types of implicit learning (e.g., perceptual, abstract, and motor) may be supported by a variety of different mechanisms, as has been shown in studies of sequence and artificial grammar learning (e.g., Meulemans & Van der Linden, 1997; Seger, 1998; Willingham, 1999). Thus, future studies are needed to better elucidate the role of perceptual processing in the matrix-scanning task.

In summary, the results from the present study suggest that perceptually based implicit learning processes are intact 1 year post head injury, despite neuropsychological impairments in other domains, specifically explicit learning and memory. Although CHI participants exhibited slower RTs than controls, both groups demonstrated faster RTs over successive covariation trials and a marked disruption when a transfer occurred. Additionally, both groups exhibited recovery following the transfer when Covariation A was reinstated. Both groups also exhibited retention for the covariation over a delay. Further, this learning occurred in spite of participants' lack of conscious knowledge for the covariation.

Thus, although the current findings suggest that implicit learning in patients with severe CHI includes the perceptual domain, it remains to be seen whether these abilities remain intact following a severe CHI or whether they are abilities that are recovered during the 1st year postinjury. Although one study has demonstrated that patients with severe CHI are able to learn motor skills during PTA (Ewert, Levin, Watson, & Kalisky, 1989), future studies should consider investigating other implicit abilities in patients with severe CHI prior to 1 year postaccident. Such studies could provide valuable insights into the mechanisms of structural pathology following head injury, as well as shed further light on the neural mechanisms responsible for implicit learning processes. Furthermore, the present results have potential implications for remediation following head trauma. At present few, if any, studies have attempted to apply implicit learning research in rehabilitative and real-world settings, particularly for patients following CHI. From the current findings it could be hypothesized that over time, patients with severe CHI could learn to implicitly associate stimulus cues in their environment with a specific behavior or outcome. For example, patients with CHI could perhaps implicitly learn to associate looking or writing in a memory notebook with environmental cues repeatedly presented over time. This remains, however, an area of further exploration.

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