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An ERP analysis of implicit structured sequence learning

KENNETH B. BALDWIN AND MARTA KUTAS
Department of Cognitive Science, University of California-San Diego, La Jolla, USA

Abstract

When task exposure facilitates performance without producing corresponding changes in verbalizable knowledge, learning is said to be implicit. In Experiment 1, event-related potentials (ERPs) were recorded as individuals practiced an implicit structured sequence learning (ISSL) task wherein only some target events required a response. With practice, the ERPs to targets that obeyed the underlying grammar diverged from those that did not at around 200 ms; grammatical targets appeared to be more positive between 200 and 500 ms because a similar positivity for the ungrammatical targets was delayed. In Experiment 2, the grammar was simplified allowing a direct comparison to be made between an implicit learning group and an explicit group, who were taught the grammar prior to recording. The results of the comparison revealed a remarkable similarity but did implicate at least partially nonidentical neural mechanisms in implicit and explicit structured sequence learning.

Descriptors: Implicit structured sequence learning, P300, Implicit learning, Awareness ERP

There is mounting evidence from neuropsychological studies of amnesia for the existence of multiple memory systems. Despite being severely impaired on conventional memory tests such as recall, cued recall, and recognition, amnesic patients are unimpaired on indirect memory measures, like priming, which do not require any conscious recollection (for reviews, see Richardson-Klavehn & Bjork, 1988; Schacter, 1987). Squire and his colleagues have argued that explicit recollection is a property of a declarative hippocampal memory system, which is damaged in amnesia, whereas the heterogeneous indirect memory phenomena can be attributed to a procedural (or nondeclarative) memory system (or systems), mediated by spared structures such as the neocortex, striatum, cerebellum, and amygdala (Cohen & Squire, 1980; Shimamura & Squire, 1989; Squire, 1992; but see Roediger & Blaxton, 1987, for a contrasting view).

It is a logically independent question, however, whether there exist dissociable learning systems that supply these memory systems with information. There is some weak evidence for this dissociation from the amnesia literature. Milner and colleagues demonstrated in the 1960s that the profoundly amnesic patient H.M. could acquire motor skills such as pursuit rotor and mirror tracing, despite being unable to remember explicitly that he had previously performed the task (Milner, Corkin, & Teuber, 1968). Since that time, amnesic patients have been shown to exhibit normal or near-normal learning in a variety of motor, perceptual, or cognitive tasks, again without any conscious recollection of having practiced them (for review, see Schacter, 1987). Although these data are suggestive, they offer no direct evidence indicating that the original learning was not accompanied by awareness; these data merely demonstrate that the acquired knowledge is implicit.

Recently, robust implicit learning has been claimed for normal individuals in three different experimental paradigms: artificial grammar learning, complex system control, and structured sequence learning. However, although individuals show a reliable dissociation between performance and reportable knowledge in all three cases, the level of concomitant awareness remains controversial. Reber (1967) was the first to demonstrate implicit learning of an artificial grammar. Individuals were instructed to memorize strings of letters in what was touted as a rote memory experiment. Unbeknownst to these participants the letter strings were generated by an artificial grammar. Following the study phase, the participants were informed of the rule-governed nature of the stimuli and were asked to make grammaticality judgments regarding novel strings. The participants were much better at this task than would be expected chance, even though they were unable to report the rules underlying their decisions of well-formedness. This basic finding has been replicated by many authors (Brooks, 1978; Dulany, Carlson, &

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Address reprint requests to: Marta Kutas, Department of Cognitive Science, University of California-San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0515, USA. E-mail: kutas@cogsci.ucsd.edu.

Dewey, 1984; Howard & Ballas, 1980; Mathews et al., 1989; Millward, 1981; Morgan & Newport, 1981).

Results of other studies, however, have suggested that individuals have greater conscious access to their acquired knowledge than was originally reported (Reber, 1967). Dulany, Carlson, and Dewey (1984), for example, asked individuals to indicate which portions of the test strings were crucial in determining their grammaticality judgments by underlining the parts that made them grammatical and crossing out the parts that made them ungrammatical. The authors found that the fragmentary rules implied by the responses predicted judgement accuracy extremely reliably and argued, therefore, that the individuals were capable of consciously stating the rules they were using to classify strings. Perruchet and Pacteau (1990) provided further evidence that performance in the artificial grammar learning paradigm results in fragmentary conscious knowledge of the bigrams constituting the grammatical strings rather than in an unconscious structured representation of the grammar (cf. Reber, 1989). The authors showed that the grammaticality judgments of participants who studied full strings did not differ from the judgments made by those exposed to a list of the bigrams making up those strings. They also found that judgments about ungrammatical strings made up of legal bigrams placed in invalid locations were extremely poor and that individuals' explicit performance on a recognition test of legal bigrams appeared sufficient to account for their performance on a standard test of grammaticality (cf. Dienes, Broadbent, & Berry, 1991; Servan-Schreiber & Anderson, 1990).

Broadbent and colleagues also have argued for distinct implicit and explicit learning modes based on a variety of complex system control tasks (Berry & Broadbent, 1984, 1987, 1988; Broadbent, FitzGerald, & Broadbent, 1986; Hayes & Broadbent, 1988). In one such task, participants were required to reach and maintain specified levels of sugar output by varying the number of workers in a sugar factory. Practice led to improved performance but had no impact on participants' ability to answer postexperiment written questions about the relationship between the input and output variables (Berry & Broadbent, 1984).

Again, however, recent studies indicate that individuals may have conscious access to a significant amount of their acquired knowledge. Marescaux, Luc, and Karnas (1989) found that performance on a postexperiment questionnaire was significantly improved if participants were questioned about situations they had actually encountered during training rather than about novel situations, suggesting that questionnaire performance is based in part on memory for specific interactions with the system. Stanley, Mathews, Buss, and Koetler-Cope (1989) asked individuals to practice a process control task and then to explain to a novice how to control the system. Moderate levels of performance were not associated with increased verbalizable knowledge, but highly practiced individuals were able to give useful instructions. However, good levels of performance still emerged well before these participants were able to communicate their knowledge.

Consistent and robust implicit learning results have been obtained in structured sequence learning paradigms in which individuals are asked to respond to the structured motion of an object through different spatial locations on a computer screen. Reaction time (RT) measures indicate that individuals rapidly acquire knowledge of the sequential patterns inherent in the stimuli and are able to use this knowledge to facilitate their responses, despite being unable to articulate what they have learned (Cleeremans & McClelland, 1991; Cohen, Ivry, & Keele, 1990; Lewicki, Czyzewska, & Hoffman, 1987; Lewicki, Hill, & Bizot, 1988; Nissen & Bullemer, 1987).

Once more, there is reason to question whether individuals may not have more conscious access to their acquired knowledge than was previously reported. Perruchet, Gallego, and Savy (1990) argued, for example, that performance may be accounted for by sensitivity to the frequency of particular subsequences, and hence the failure of persons to report the generative rule in a postexperiment debriefing does not demonstrate a lack of awareness of the information underlying their behavior. Recently, Perruchet, and Amorim (1992) demonstrated that individuals could successfully produce valid fragments of the sequence used in training in a free generation task when they were instructed to generate a sequence of trials that looked like the sequence encountered during training. It is unclear, however, whether this ability is based on conscious knowledge per se; perhaps these participants did not know why they felt compelled to press the keys in a certain order.

In sum, robust data from three different implicit learning paradigms have demonstrated a dissociation between task performance and reportable knowledge, but the level of the individual's concomitant awareness remains uncertain. Shanks and St. John (1994) pointed out that the difficulty in interpreting a dissociation between performance and reportable knowledge stems from three methodological weaknesses in virtually all implicit learning paradigms. First, postlearning tests of awareness can never provide more than weak evidence for the state of awareness during learning itself. For example, the fact that amnesic patients cannot verbalize their acquired knowledge, indeed do not even recall having practiced a task before, does not necessarily mean that the original learning was unconscious.

Second, we must be certain that the tests of performance and awareness are equally sensitive so that better performance in a test of performance than in a test of explicit knowledge does not merely reflect the greater sensitivity of the former. Verbal report, the most commonly used test of awareness, provides almost no retrieval cues and is, hence, almost certainly less sensitive than performance measures.

Third, although the question of level of awareness during implicit learning is logically independent of the question of what knowledge has been acquired during practice, these questions are not methodologically independent. The availability of acquired knowledge to an individual's awareness cannot be properly assessed without first determining the exact nature of that knowledge. Otherwise, the awareness tests (e.g., a postexperiment debriefing) may be asking for information different from what is in fact responsible for facilitated performance. The failure to demonstrate such awareness logically would not imply that individuals are unaware of the information that actually underlies their behavior (cf. Perruchet & Pacteau, 1990).

On the basis of these three methodological concerns, Shanks and St. John (1994) concluded that although a dissociation between task performance and postperformance measures of reportable knowledge is now well established, it provides no evidence at all for the functional dissociation of conscious and unconscious learning. Recording the concomitant neuroelectric activity of the brain during implicit learning, however, represents a potentially significant methodological advance. Because event-related brain potentials (ERPs) can be passively recorded concurrent with task performance, there is no need to make a backwards inference concerning any obtained ERP effects. Of course, however, there is the mapping problem of determining exactly which function is being reflected by the measure, which is inherent in any brain imaging technique. With this caveat in mind, we can directly compare the ERPs elicited under putatively conscious and unconscious performance conditions, as measured by (methodologically suspect) postperformance tests of awareness, and we can take a difference as indicative of functionally different processing during performance. The lack of a difference would be more difficult explain because a generator with a closed field configuration, for example, would not be discernible at the scalp.

Although the ERP methodology might be productively applied to all three basic implicit learning paradigms, implicit structured sequence learning (ISSL) is the most amenable to such a technique. Unlike artificial grammar learning, ISSL is a continuous on-line process well suited to the passive recording of brain waves, and unlike some process control paradigms, ISSL tasks require persons to make only simple and therefore rapid decisions at each time step. Thus, there were two research goals of this paper. The first was to isolate the ERP correlates of performance in an ISSL task (Experiment 1). Second, once these correlates were isolated, they were subsequently used as dependent measures to determine whether or not performance (and by inference learning) with explicit knowledge differs from implicit learning (Experiment 2).

EXPERIMENT 1

A variety of similar ISSL paradigms have been reported; these differ in their specific stimulus-response characteristics and in the complexity of the underlying structure. An elegant variant introduced by Cleeremans and McClelland (1991) required individuals to perform a serial RT task to rule-governed (grammatical) sequential stimuli containing noise (occasional ungrammatical trials). This added noise allowed a direct comparison of the RTs to each type of trial during the course of practice and hindered individuals' abilities to detect the regularities explicitly. The Cleeremans and McClelland paradigm, however, has some stimulus-response characteristics not ideally suited to ERP recording. The eyes, tongue, and musculature can all generate electrical activity that will contaminate the electroencephalogram (EEG) and may or may not be time locked to the stimulus events. To some extent, these artifacts can be controlled through careful instructions and by rejecting trials containing noncerebral potentials, but we took the further precaution of modifying Cleeremans and McClelland's paradigm to eliminate large lateral eye movements and an obligatory motor response on every trial without altering the basic experimental logic. Specifically, rather than presenting six lights in a horizontal line spanning 15 cm, the stimuli appeared in a 3 x 3 grid (5-cm square). Additionally with ERPs as a dependent variable, it was possible to look at each event as the sequence was presented whether or not the participant actually made an RT response; target stimuli that required a speeded response were incorporated to afford a replication of the known behavioral effects, and so-called standard or nontarget stimuli that required no overt response were also included. Both targets and nontargets appeared in certain locations according to the same underlying grammar (and violations thereof). Thus, in principle, this design allowed us to examine the role of the response in the implicit learning during ISSL, thereby potentially revealing more about what actually was being learned.

Thus, the objectives of Experiment 1 were to replicate Cleeremans and McClelland's (1991) implicit learning effect under the modified conditions and to isolate the ERP correlates of this behavioral effect. To the extent that these correlates resemble known brain wave componentry elicited in other experimental paradigms, they may help to elucidate the nature of the cognitive processes underlying ISSL.

Methods

Participants. Nine right-handed students (eight men, one woman) were each paid $75 to participate in the five sessions of the experiment and received a bonus of up to $25 on the basis of their performance. All had normal or corrected-to-normal vision, and all were right handed (five had left-handed relatives). Participants ranged in age from 19 to 30 years.

Design and procedure. Participants were tested one at a time in a sound-attenuating chamber. They were instructed to monitor the apparent movement of an object within a 3 x 3 grid (5 cm^2) in the center of a computer screen approximately 80 cm in front of them while they reclined in a comfortable chair. The object, a small green square, was displayed for 790 ms at a particular location, followed by a 10-ms interval; then it would reappear at another location.

Participants were told that the movement of the object within the grid was random. In fact, the movement was governed by a finite state grammar (Figure 1). Finite state grammars consist of nodes connected by labeled arcs. Sequences are generated by starting at a particular node, randomly choosing an emanating arc, traveling that arc, recording the associated label, then repeating the process for the subsequent node. The grammar loops back onto itself; the leftmost and rightmost nodes, both labeled 0, are the same. Once the generation procedure is begun, therefore, the grammar produces a continuous string of labels until the process is terminated.

The vocabulary consisted of nine labels, each appearing twice in the grammar with no direct repetitions. Because identical labels could be preceded by different contexts as a function of their position in the grammar, the resultant sequence was highly context dependent. The predictability of the grammar was such that all nine labels were equiprobable in the absence of contextual information, four labels were equiprobable given the prior label, and two labels were equiprobable given the prior two

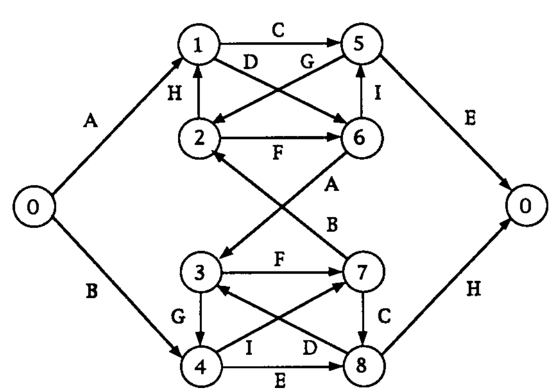

Figure 1. The finite state grammar used to generate the stimulus sequences in Experiment 1.

labels. No greater predictability was possible given contexts of length greater than two. Ungrammatical labels were randomly substituted on 15% of the trials, again with no direct repetitions.

The labels were randomly mapped onto the nine screen locations for the first participant and then varied systematically in a 9 x 9 Latin square design so that each label was assigned to every location once across the nine participants. Thus, the sequence of labels was translated into a sequence of screen locations; participants were never presented with the actual labels of the grammar.

During each block of trials, participants were told to respond with a single button press, using their dominant hand, to one of the four possible types of apparent motion in this 3 x 3 grid: horizontal (left or right), vertical (up or down), diagonal (as a bishop would move in chess), or "knight's move" (as a knight would move in chess). The target motion was selected randomly for each block, with the constraint that there were an equal number of each type per hour. Both speed and accuracy were stressed.

There were 32 blocks of 185 trials each per 2-hr session. Each block was initiated by a *get ready* message and followed by speed and accuracy information. The first five trials of each block were random in order to eliminate initial variability in the responses; data were not recorded from these trials. Participants were given a 1-min rest between blocks and a 10-min break in the middle of the session. Five such practice sessions were held over 5-6 consecutive days. Bonus money was calculated, per block, as follows: plus $0.001 for each millisecond of RT under 425 ms, minus $0.001 for each millisecond over 425 ms, plus $0.01 for each percentage point of accuracy over 95%, and minus $0.01 for each percentage point under 95%. Bonus money acquired on one block could not be lost on subsequent blocks, and no more than $2.50/hr in bonus money could be earned.

Postexperimental debriefing. Explicit knowledge of the stimulus structure was assessed via a postexperiment written questionnaire. After participants were informed of the nonrandom nature of the stimulus sequences, they were given a prediction test. Each question (72 total) gave them a permissible sequence of two movements for the object, and they were instructed to indicate where they thought the object would go next: "Although in some cases you may have a strong sense of where the object will move next, in other cases you may have no idea. Try to imagine the given movements in your head and simply make your best guess about the continuation. Please answer every question." Given that the object must move to a new location, there were eight possible answers to each question. Because responses were scored as correct if participants provided either of the two possible grammatical continuations, chance performance was 25% correct.

Electrophysiology. EEG was recorded throughout training from International 10-20 electrode sites 173/4, F7/8, C3/4, Cz, P3/4, T5/6, and 01/2. An additional electrode was placed over the right mastoid, and vertical eye movements and blinks were monitored via an electrode placed below the right eye. All scalp sites and the vertical electrooculogram electrode were referenced to the left mastoid. Horizontal eye movements were monitored via a right to left bipolar montage at the external canthi of the two eyes. The EEG was amplified by a Grass Model 12 Neurodata Acquisition System with half-amplitude cutoffs of 0.01 and 100 Hz and were digitized on line at a sampling rate of 250 Hz. Trials characterized by excessive eye movements, muscle contractions, or amplifier blocking were rejected prior to averaging.

Results

Task performance. There was a general decrease in RT with practice and an increasing facilitation for grammatical trials relative to ungrammatical trials (Figure 2). During the final session, the mean facilitation effect was 47 ms. Mean RTs for each participant were subjected to a 5 x 4 x 2 analysis of variance (ANOVA) with repeated measures, using session (5), motion type (4), and grammaticality as within-subject variables. There were significant main effects of session, $F(4,32) = 114.39$, $p < .0001$, $e = 0.73$, and grammaticality, $F(1,8) = 187.30$, $p < .0001$, and a significant interaction of Session x Grammaticality, $F(4,32) = 9.20$, $p < .002$, $e = 0.57$.

The four types of motion discrimination differed in their difficulty, as judged by the mean RTs. Participants were slower on average to respond to knight's move targets (391 ms) than to diagonal targets (356 ms), slower to respond to diagonal targets than to horizontal targets (342 ms), and slower to respond to horizontal targets than to vertical targets (318 ms), main effect of motion type, $F(3,24) = 42.36$, $p < .0001$, $e = 0.54$ (no Motion Type x Session interaction).

The effect of grammaticality varied with the task difficulty; it was largest during the fifth session for knight's move (83 ms), intermediate for diagonal (53 ms), and small for horizontal and vertical (27 and 25 ms, respectively), Motion Type x Grammaticality interaction, $F(3,24) = 8.57$, $p < .0005$, $e = 0.68$. Separate ANOVAs were conducted for each target type. All four motions showed a significant main effect of grammaticality ($p < .001$), but only diagonal and knight's move showed a significant interaction of Session x Grammaticality ($p < .01$).

Postexperimental debriefing. Participants displayed poor, although marginally better than expected by chance, declarative knowledge of the stimulus structure on the postexperiment explicit prediction questionnaire. All nine participants scored

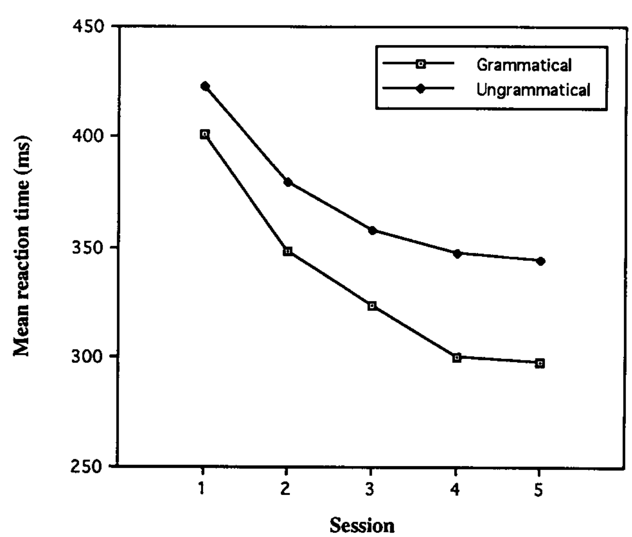

Figure 2. Mean reaction times for grammatical and ungrammatical trials for each of the five practice sessions of Experiment 1.

above the chance level (25%); the mean performance was 30.6% (SD = 3.1%).

Electrophysiology. The ERPs for nontarget (standard) motions displayed a broad positive-going component, peaking at about 300-400 ms poststimulus. The targets elicited a similar, although larger, positivity. Both positivities increased in amplitude with practice. The ERPs for each participant were quantified by their mean amplitude within the 200-500-ms latency window relative to a 100-ms prestimulus baseline and subjected to a 5 x 2 x 2 x 6 ANOVA with repeated measures, using session, stimulus type (target or standard), hemisphere (2), and electrode site (6) as within-subject variables. There were significant main effects of session, $F(4,32) = 8.12$, $p < .003$, $e = 0.53$, and stimulus type, $F(1,8) = 5.65$, $p < .04$. Although the positivity for the standards appeared to increase in amplitude with practice at a faster rate than that for the targets, the Session x Stimulus Type interaction was not significant.

The difference between target and standard ERPs revealed a classic P300 component (for review, see Hillyard & Picton, 1987), largest over centroparietal scalp locations, which appeared to decrease in amplitude with practice (because of the faster increase in the positivity elicited by the standards).

A comparison of ERPs to grammatical versus ungrammatical trials revealed that between 200 and 500 ms grammatical trials were more positive. A 5 x 2 x 4 x 2 x 2 x 6 ANOVA with repeated measures was performed on mean amplitude measurements, using session, stimulus type, motion, grammaticality, hemisphere, and electrode site as within-subject variables. There was a significant main effect of grammaticality, $F(1,8) = 13.44$, $p < .001$, and an interaction between stimulus type and grammaticality, $F(1,8) = 47.37$, $p < .001$.

A comparison of target and standard trials revealed a robust effect of grammaticality only for targets, with a small, earlier reversed effect during blocks where a response was not required to those same motions (Figure 3). Separate ANOVAs performed on standard and target trials found a significant main effect of grammaticality only for targets, $F(1,8) = 41.53$, $p < .001$. However, an ANOVA for the standards did show significantly greater positivity for the ungrammatical than for the grammatical trials between 250 and 350 ms, $F(1,8) = 24.47$, $p < .005$.

The analysis of the target trials also revealed a marginally significant interaction of grammaticality and motion type, $F(3,24) = 3.06$, $p < .07$, $e = 0.64$. The effect of grammaticality followed a similar pattern of interaction with task difficulty as the RTs, being largest for knight's move, intermediate for diagonal and horizontal, and small for vertical (Figure 4, shaded area). Separate ANOVAs performed on targets of each motion type found a significant main effect of grammaticality ($p < .01$) for all motions except vertical. Figure 5 shows the grammaticality difference wave for the knight's move targets during the fifth session. The differential peaks at about 400 ms poststimulus and is largest over parietocentral sites, main effect of electrode site, $F(5,40) = 11.44$, $p < .0007$, $e = 0.42$ (no main effect of hemisphere). Despite a visible trend in the data, none of the ANOVAs revealed a significant interaction of Session x Grammaticality. This trend appeared to be due primarily to an increasing positivity for the grammatical trials rather than greater negativity for the ungrammatical trials.

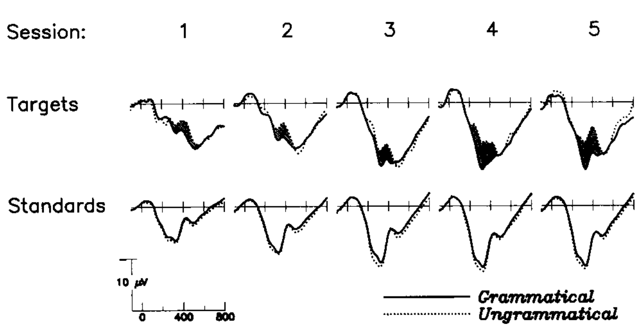

Figure 3. Grand average ERPs elicited by grammatical and ungrammatical target and standard motions for each of the five practice sessions of Experiment 1 (knight's move targets, all standards; site = vertex or Cz).

Discussion

The first objective of this experiment was to replicate Cleeremans and McClelland's (1991) implicit learning effect in a design slightly modified to accommodate the ERP technique. RT analysis did indeed show an increasing facilitation with practice for grammatical relative to ungrammatical trials, indicating that participants acquired knowledge of the sequential patterns inherent in the stimuli and were able to make use of this knowledge to facilitate their responses. This learning may be termed "implicit," in a purely operational sense, because participants performed poorly on the postexperiment explicit prediction task, thus demonstrating a dissociation between their skilled performance and their verbalizable knowledge, although their marginally above-chance scores on the prediction test suggest perhaps at least some explicit knowledge of a few highly salient subsequences.

The implicit learning effect, furthermore, varied with the difficulty of the motion discrimination (as measured post hoc by mean RTs to each of the four motion types). The facilitation effect was largest for the knight's move targets, intermediate for

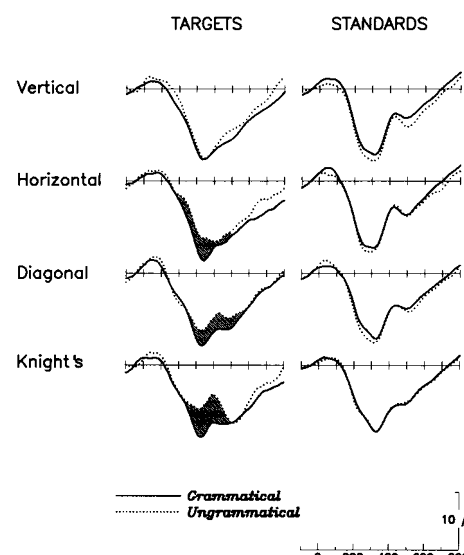

Figure 4. Grand average ERPs elicited by grammatical and ungrammatical target and standard motions for each of the four motion types during the fifth session of Experiment 1 (site = Cz).

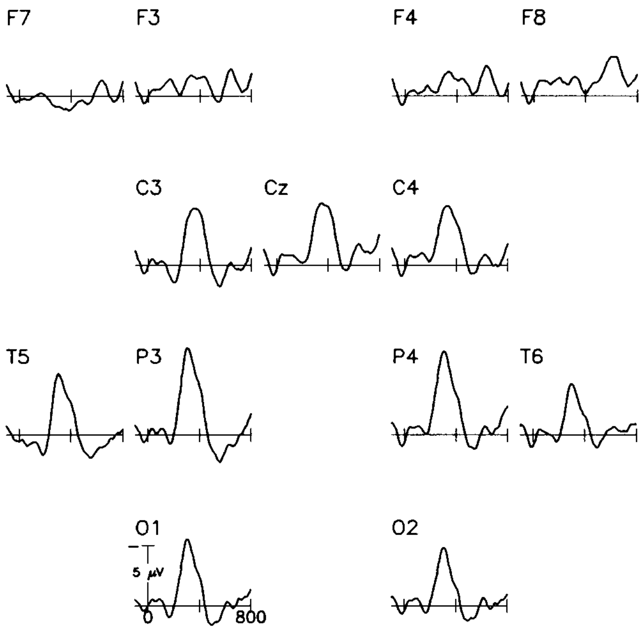

Figure 5. Difference waves produced by subtracting the grand average ERPs elicited by grammatical trials from the ungrammatical trials for knight's move targets during the fifth session of Experiment 1 (site = Cz).

the diagonal targets, and small for horizontal and vertical targets. Hartman, Knopman, and Nissen (1989) made a related observation in their study of implicit learning of a repeated sequence of verbal stimuli. They found that when individuals were given a highly automatic and overlearned task (word naming), little implicit learning occurred, but when a more effortful task was used (semantic categorization), robust learning was observed. They argued that effortful tasks require greater attention, in the sense that individuals must actively process a stimulus so they can map it onto its appropriate response, in contrast to automatic tasks that permit adequate performance as long as individuals are merely oriented to the stimulus. Hence, Hartman et al. suggested that attention is an important prerequisite for implicit learning, despite the supposed lack of conscious awareness.

This interpretation is consistent with results from several dual task studies. Nissen and Bullemer (1987) demonstrated that no implicit learning of a repeating spatial sequence occurred when individuals performed a memory-intensive secondary task concurrently. In a follow-up study, Cohen et al. (1990) found that only sequences in which items are not entirely predictable based on their immediate predecessor are difficult to learn under dual task conditions. The grammar used to generate the stimuli in the current experiment is probabilistic; perfect prediction is never possible, so the resultant sequences are complex by Cohen et al.'s standard.

But because the naming and categorization tasks used by Hartman et al. (1989) differ in ways other than their effortfulness, they were forced to acknowledge that the nature of the categorization task might have enabled implicit learning. This alternative hypothesis, however, seems less compelling in the current experiment, where all four tasks are motion detections. Thus, the Learning x Difficulty interaction is most likely due to the less automatic nature of the more difficult motion detections.

Having replicated the implicit learning effect, the second objective of this experiment was to isolate the ERP correlates of this behavioral effect. The relative difference between ERPs elicited by target and standard motions revealed a P300 component (for review, see Hillyard & Picton, 1987); as expected, the rarer target motions elicited greater positivity than did the standard motions. The amplitude of the target-minus-standard P300 also appeared to decrease with practice, consistent with the observation of Kramer, Schneider, Fisk, and Donchin (1986) that the effect of stimulus probability on P300 amplitude diminished with extensive practice.

The relative difference between ERPs elicited by grammatical and ungrammatical standards (i.e., the stimuli that did not require a response) revealed a small positivity to ungrammatical targets between 250 and 350 ms, which likely reflects a kind of *expected target* effect. Ungrammatical standards consist of two subtypes: those where a target was expected and those where another standard was expected. The failure to confirm an expected target would be expected to elicit a P300. This issue was explored in more depth in Experiment 2.

The most pronounced difference between ERPs elicited by grammatical and those by ungrammatical targets was the greater positivity to grammatical trials or an apparent negativity to ungrammatical trials between 200 and 500 ms. This effect was closely correlated with performance: it emerged with practice and followed a similar pattern of interaction with task difficulty as did the RTs. This correlation is readily apparent in a three-way RT split of the grammatical targets for the knight's move during the final session (see Figure 6). In fact, this comparison suggests that when grammatical and ungrammatical events are more closely matched on RT, there appears to be no fundamental difference between the elicited ERPs; both were characterized by an N2/P3 complex. This ERP grammaticality effect, like the behavioral measure, reflects the confirmation or violation of sequential expectancy and should not be taken as an index of a storage process. Nonetheless, tracking the emergence of

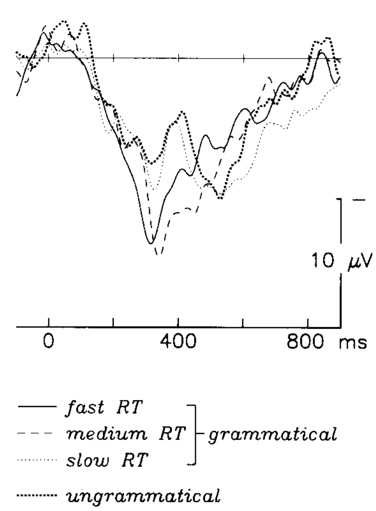

Figure 6. Final session ERPs to grammatical knight's move targets sorted as a function of reaction times contrasted with ERPs to ungrammatical knight's move targets.

such expectancies as a function of practice is ipso facto a measure of the learning of the sequential structure inherent in the task to exactly the same degree as is the standard performance measure.

The other major finding in the ERP data from this experiment was the lack of the same grammaticality effect for the standard stimuli as for the targets. By the conclusion of training, the same ungrammatical motion that elicited an N2 and a late P3 as a target, elicited only a slightly enhanced and earlier positivity on blocks where it was a standard. This target-standard effect may be an artifact of the task difficulty effect. Consider, for example, the diagonal standards. This waveform, which shows no targetlike effect of grammaticality, collapses trials where the target was horizontal, vertical, or knight's move. Perhaps a measurable effect occurs on the knight's move trials but is attenuated when these trials are pooled with trials of lesser difficulty. In fact, the target-standard effect and the task difficulty effect appear to be separate because none of the standard motions during blocks in which knight's move was the target showed a significant targetlike effect of grammaticality.

The target-standard effect could also be attentional, however. Perhaps rejecting the standard trials is a relatively shallow, effortless process, requiring the subject merely to be oriented to each stimulus, whereas response generation requires greater attention and depth of processing. Several implicit learning studies have also suggested that some aspect of making a motor response may be crucial for the encoding or expression of implicit knowledge (cf. Berry, 1991; Willingham, Nissen, & Bullemer, 1989). Because there is still no consensus as to what actually is being learned, perhaps our results suggest that a critical aspect of ISSL is tied to the response system such that if no response is made then the underlying sequence is not learned. From this view, our emphasis is not so much on the acquisition of the appropriate response but rather on a series of stimulus-response mappings. Our proposal that a response task may be required to produce learning does not entail a commitment as to whether the acquired knowledge is embedded in the response system; that is a separate question whose answer is unknown.

Several studies have demonstrated, for example, that no learning seems to occur in the absence of a response task. Willingham et al. (1989) had participants respond to random color changes of an object moving through a repeated sequence of stimulus positions. Thus, although there was no response sequence to be acquired, participants could learn to anticipate where the next stimulus would appear so they could facilitate the color discrimination. If they did so, they would have an advantage over a control group, who performed the same task but with an object moving through random locations. No such difference was observed! We also examined this issue in a variant of Experiment 1 (with five new participants), wherein all the targets for four sessions were exclusively knight's move. Thus, although participants had to view the entire sequence to perform the knight's move discrimination, they never responded overtly to horizontal, vertical, or diagonal motions. The question of interest was whether participants would acquire knowledge specific to the knight's move discrimination task or whether they would acquire general knowledge of the sequential patterns inherent in the display that would support performance in the other discrimination tasks. These possibilities were assessed by having participants respond to all four motion types during the fifth session. The results were unequivocal; there was no transfer. Only the knight's move showed a significant effect of grammaticality. These data therefore do not support the position that individuals induce passively the general rules underlying stimulus regularities (Reber, 1989).[1]

EXPERIMENT 2

In Experiment 2, the underlying grammar was simplified to the point that it could easily be taught to participants prior to the experiment so that they could hold it in consciousness while they performed the task. The question of interest was whether violations of this sort of conceptually driven explicit expectancy would elicit a qualitatively different ERP correlate than the violations of putatively implicit data-driven expectancy in Experiment 1. Conceptually driven processes refer to those that are participant-initiated, top-down activities (e.g., elaboration and reconstruction), whereas data-driven processes are determined in a bottom-up fashion by information in the stimuli (Jacoby, 1983; Roediger & Blaxton, 1987). Our aim was to answer this question by comparing the behavior and ERPs of an *implicit* group of participants, who were given no information about the underlying sequence (as in Experiment 1) and an *explicit* group, who were informed about the sequence of stimulus movements across the grid.

Methods

The postexperiment debriefing and electrophysiological recording were performed as in Experiment 1 with the following exception. The EEG was amplified with half-amplitude cutoffs of 0.1 and 100 Hz.

Participants. Twenty-four new students (16 men, 8 women) participated in the experiment, for which they were each paid $15 plus a bonus of up to $5 on the basis of their performance. All had normal or corrected-to-normal vision. Twenty-one of the participants were right handed (two had left-handed relatives). They ranged in age from 16 to 34 years.

Design and procedure. Participants practiced the task for a single 2-hr session. The target motion was selected randomly for each block, but with the added constraint that there were two of each type every eight blocks. The movement of the object within the grid was not governed by the finite state grammar used in the previous experiments. Rather, the object cycled through each of the four possible motion types in a particular order (e.g., horizontal-diagonal-knight's move-vertical [H-D-K-V]). There are six such possible motion loops. The specific sequence of locations in the 3 x 3 grid for the object was determined by randomly selecting from among the possible locations that specified a grammatical motion relative to the previous location. If, for example, the grammatical motion is horizontal, there are always two ways in which this motion may be instantiated, and the generation program randomly selected from among them.

The predictability of sequences generated in this way approximates that of the sequences used previously-perfect knowledge

[1] Under these circumstances, mean performance on the prediction task was 31.6% overall; knight's move was 42.3% and all others were 28.25%. Clearly, with such extensive practice on the knight's move, some knowledge about it was accessible to verbal prediction.

of the preceding context usually limits the grammatical continuations to two equiprobable locations. The slight variance from this rule is due to peculiarities associated with the center location, from which four diagonal motions and no knight's moves are possible. The generation program was designed to look one motion ahead, and to systematically bias its choices to avoid having to make an (impossible) knight's move from the center. Finally, ungrammatical movements were randomly substituted in 15% of the trials.

Although the motion loops are extremely simple, they generate complex series of locations. For example, beginning in the upper left corner of the grid, the sequence H-V-D can be instantiated in 10 different ways and can reach any location in the grid. This fact, coupled with the additional noise, makes it very difficult for uninformed individuals to detect the stimulus regularities. However, the grammar is sufficiently simple that individuals can be quickly taught the pattern and can hold it in consciousness while they perform the task.

The 24 participants were divided into two groups of 12. In the explicit condition, participants were informed at the outset of the experiment of the specific motion loop that they would experience and were encouraged to use this information to facilitate their task performance by anticipating the object's movement. As a reminder, the pattern (e.g., H-D-V-K) was displayed at the bottom of the grid. The 12 participants in the implicit condition were told that the object's movement was random. The six possible loops were varied systematically so that each pattern was used for two participants in each condition.

Results

Task performance. For purposes of RT analysis, the 2-hr experimental session was subdivided into four half-hour periods of eight blocks each to test for practice effects. Mean RTs for each participant were subjected to a 2 x 4 x 4 x 2 ANOVA with repeated measures, using instruction set (implicit vs. explicit) as a between-subjects variable and period (4), motion type (4), and grammaticality as within-subject variables. Reaction times decreased with practice, main effect of period, $F(3,66) = 24.26$, $p < .0001$, $e = 0.76$, and participants in the explicit group were faster to respond overall than were those in the implicit group, main effect of instruction set, $F(1,22) = 4.41$, $p < .05$, but the interaction between period and instruction set was only marginally significant ($p = .068$).

Participants were faster overall to respond to grammatical trials than ungrammatical trials. There was a significant main effect of grammaticality, $F(1,22) = 177.50$, $p < .001$, and a significant interaction between instruction set and grammaticality, $F(1,22) = 20.75$, $p < .001$. Explicit participants were faster to respond to grammatical trials than were implicit participants, but their RTs to ungrammatical trials did not differ (Figure 7). The grammaticality effect also increased with practice, Grammaticality x Period interaction, $F(3,66) = 7.63$, $p < .001$, $e = 0.71$, slightly more rapidly for the explicit than for the implicit group, Grammaticality x Period x Instruction Set interaction, $F(3,66) = 2.68$, $p < .07$, $e = 0.71$.

Ungrammatical trials also can be broken down into three subtypes on the basis of their degree of association with the grammatical continuation that they replace. For example, if the generative motion loop is H-D-K-V and the preceding context ended with a knight's move, vertical is the grammatical continuation (85% probability of occurrence). Horizontal, diagonal, and knight's move are all equally ungrammatical in terms of their probability of occurrence (5% each). They differ, however, in their degree of association with vertical: horizontal being the strongest because it typically follows vertical, diagonal being intermediate because it typically follows horizontal, and knight's move being the weakest. We will distinguish between these levels of association by their *lag-one,* two, or three steps, respectively. Reaction times were sensitive to the degree of association for the ungrammatical trials: the greater the lag, the slower the RT. Separate pairwise comparisons found that all differences within each condition were significant ($p < .005$). Pairwise comparisons between implicit and explicit conditions found a significant difference only for the grammatical trials, $F(1,22) = 13.46$, $p < .005$.

The four types of motion discrimination differed in their difficulty, as judged by the mean RTs. Participants were faster on average to respond to diagonal targets than to knight's move targets and faster still for horizontal and vertical, main effect of motion type in the complete ANOVA, $F(3,66) = 50.17$, $p < .0001$, $e = 0.63$. The effect of motion type did not interact significantly with practice or instruction set. The effect of grammaticality varied with motion type in a mixed pattern: decreasing with increased task difficulty from horizontal to vertical to diagonal movements, then increased for knight's move, Grammaticality x Motion Type interaction, $F(3,66) = 2.81$, $p < .05$, $e = 0.83$. This pattern did not interact significantly with instruction set. There was, however, a slight tendency for greater learning for the knight's move targets, Grammaticality x Motion Type x Period, $F(9,198) = 2.14$, $p < .06$, $e = 0.53$.

Postexperimental debriefing. Participants in the explicit group completed the postexperiment explicit prediction test with a mean accuracy of 96.8% (SD = 4%). Theoretically, they only needed to apply the generative rule they had been taught to achieve perfect performance, but most participants (8/12) did make a few errors. Implicit group participants displayed poor, although marginally better than expected by chance (25%), explicit knowledge of the stimulus structure on the prediction ques-

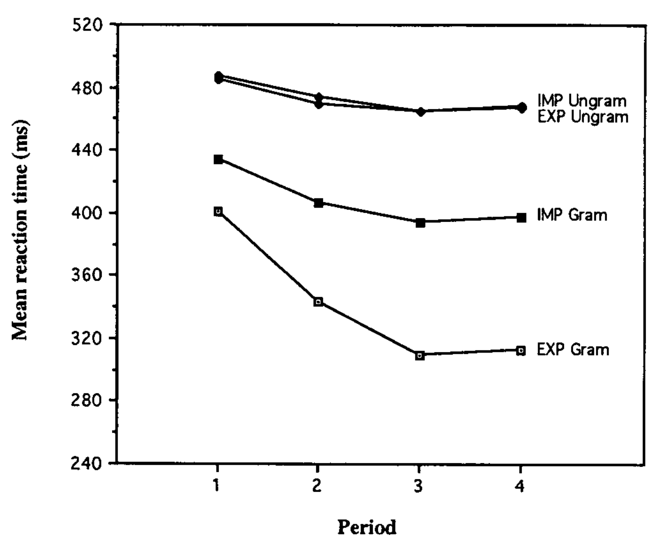

Figure 7. Mean reaction times for grammatical and ungrammatical trials under implicit and explicit conditions for each of the four half-hour practice periods of Experiment 2.

tionnaire. The mean performance was 28.1% (SD = 3.4%). A planned pairwise comparison of accuracy scores using instruction set (implicit vs. explicit) as a between-subjects variable was, as expected, significant, $F(1,22) = 2039.26$, $p < .001$.

Electrophysiology. The ERPs for standard motions displayed a broad positive-going component, peaking at about 300 ms poststimulus. The targets elicited a larger positivity peaking at the same latency, which increased in amplitude with practice. The ERPs for each participant were quantified by their mean amplitude within the 200-500-ms latency window relative to a 100-ms prestimulus baseline and subjected to a 2 x 4 x 2 x 2 x 6 ANOVA with repeated measures, using instruction set (implicit vs. explicit) as a between-subjects variable and period (4), stimulus type (target or standard), hemisphere (2), and electrode site (6) as within-subject variables. There were significant main effects of stimulus type, $F(1,22) = 121.6$, $p < .001$, and period, $F(3,66) = 5.93$, $p < .005$, e = 0.75, and a significant interaction between stimulus type and period, $F(3,66) = 5.50$, $p < .002$, e = 0.85.

The relative difference between targets and standards revealed a P300 effect, largest over centroparietal scalp locations, that appeared to increase slightly in amplitude with practice. The target-standard effect also appeared to be delayed in latency on ungrammatical movements relative to grammatical movements and to be slightly larger for the explicit than implicit participants (Figures 8 and 9), although this difference was not significant.

A comparison of ERPs to grammatical versus ungrammatical trials showed greater positivity to ungrammatical trials between 250 and 350 ms for the standards and greater positivity to the grammatical trials between 200 and 500 ms for the targets (Figure 10). Separate 2 x 2 x 2 x 6 ANOVAs with repeated measures were performed on mean amplitude measurements for each stimulus type within the appropriate latency window, using instruction set as a between-subjects variable and grammaticality, hemisphere, and electrode site as within-subject variables. There were significant main effects of grammaticality in both cases, standards: $F(1,22) = 16.95$, $p < .001$; targets: $F(1,22) = 89.28$, $p < .001$, but no significant main effect of instruction set or interactions with instruction set, despite a visible trend for a larger target grammaticality effect for explicit relative to implicit participants.

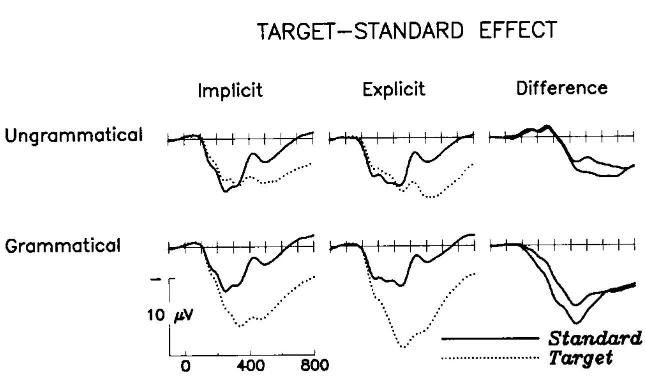

Figure 8. Grand average ERPs elicited by target and standard motions for grammatical and ungrammatical trials under implicit and explicit conditions (Experiment 2; site = Cz). The difference waves were produced by subtracting the standard from the target ERPs within each cell.

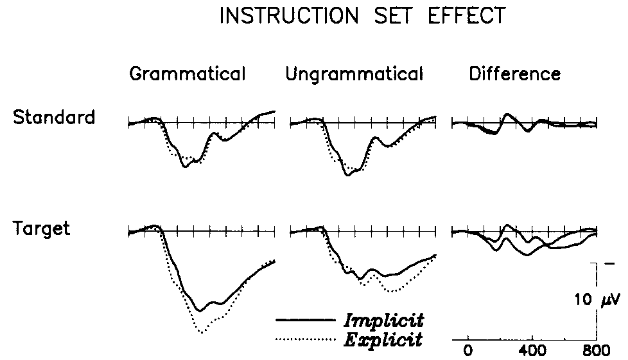

Figure 9. Grand average ERPs elicited by trials under implicit and explicit conditions for grammatical and ungrammatical target and standard motions (Experiment 2; site = Cz). The difference waves were produced by subtracting implicit from explicit ERPs within each cell.

Ungrammatical trials can be broken down into three subtypes on the basis of their degree of association with the grammatical continuation that they replace, even though they are equal in their probability of occurrence. A comparison of the ERPs elicited by ungrammatical targets of each lag revealed greater positivity in the 200-500-ms latency window as a function of decreasing lag for both explicit and implicit groups. Separate pairwise comparisons on mean amplitude measurements confirmed that all differences within each condition were significant ($p < .05$), except for the difference between grammatical and ungrammatical trials of lag = 1 for the implicit group ($p = .09$). Pairwise comparisons between conditions found no significant difference for any trial types despite the trend noted previously for grammatical trials to elicit greater positivity under explicit conditions.

The ERP effect of grammaticality did not significantly interact with task difficulty, although it appeared to vary with motion type in the same mixed pattern as the reaction times: decreasing with increased task difficulty from horizontal to vertical to diagonal movements and then increased for knight's move. The target ERPs were quantified by their mean amplitude within the 200-500-ms latency window and subjected to a 2 x 4 x 2 x 2 x 6 ANOVA with repeated measures, using instruction set as a between-subjects variable and motion type (4), grammaticality, hemisphere, and electrode site as within-subject variables. There were significant main effects of motion type, $F(3,66) = 20.87$, $p < .0001$, e = 0.71, and grammaticality, $F(1,22) = 88.88$, $p < .001$, but no Motion Type x Grammaticality interaction. Separate ANOVAs performed on targets of each motion type found a significant main effect of grammaticality ($p < .01$) in all cases.

Overlap correction. As seen in Figure 6, ERPs to the grammatical targets with the slowest RTs were remarkably similar to ERPs for ungrammatical targets. Because our primary aim in this experiment was to compare implicit and explicit learning, we again were obliged to consider (and control for) the difference in RTs between the two conditions. To compare them directly, we applied an overlap correction procedure that gives an estimate of stimulus-related activity with response-related activity removed, and vice versa (Dale, Ganis, & Kutas, in preparation).

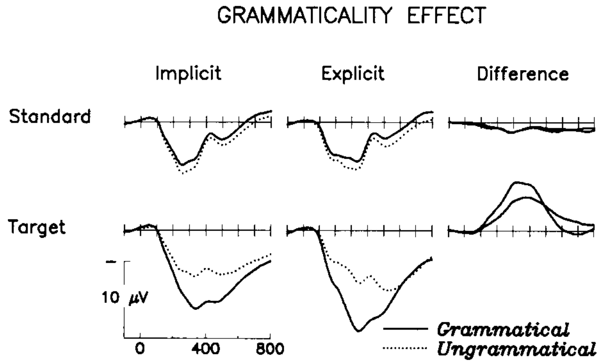

Figure 10. Grand average ERPs elicited by grammatical and ungrammatical target and standard motions for trials under implicit and explicit conditions (Experiment 2; site = Cz). The difference waves were produced by subtracting grammatical from ungrammatical ERPs within each cell.

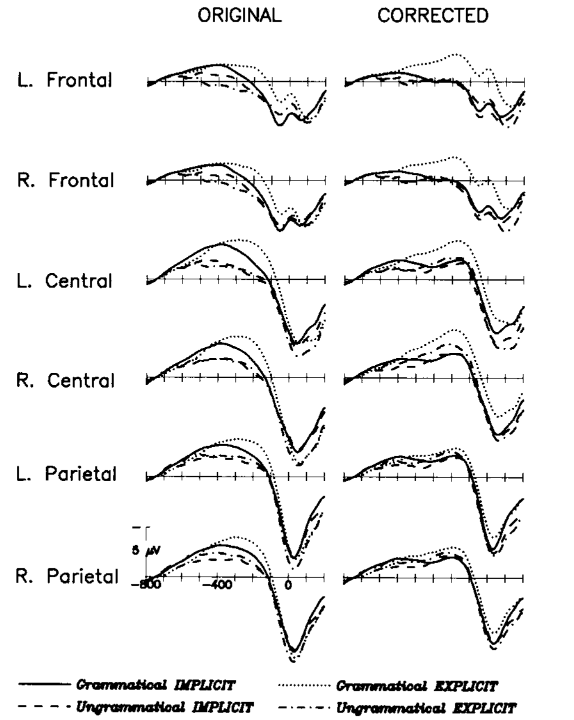

Figure 11 . Grand average original and overlap-corrected response-locked ERPs elicited by grammatical and ungrammatical target motions under implicit and explicit conditions in Experiment 2.

This procedure is related to the adjacent response (ADJAR) filter (Woldorff, 1993), which has been generalized and extended to deal with lower frequencies, greater overlap, and less jitter. The procedure exploits jittering of the interstimulus intervals (ISIs) to obtain an estimate of the "true" ERP response to one event by removing overlapping activity more closely correlated with the previous and subsequent events. In the current experiment, stimulus and response can be viewed as adjacent events separated by partially jittered ISIs, due to variability in RTs. The method solves for the ERP waveforms that, when overlapped according to interstimulus interval distributions (jitter), would yield the observed ERP. This linear problem can be solved interatively or by direct matrix inversion (Dale et al., in preparation). For the purposes of this analysis, ungrammatical trials of lag = 3 (i.e., immediate response repetitions) were excluded because they may elicit differential brain activity not strictly related to ungrammaticality per se.

The overlap-corrected response-locked ERPs displayed a slow preresponse negativity followed by a sharp positivity peaking just after the response (Figure 11). These ERPs were quantified by mean amplitude measurements within both the -400-0-ms latency window and between 0 and 200 ms, relative to a -800- to -700-ms preresponse baseline and subjected to a 2 x 2 x 2 x 6 ANOVA with instruction set as a between-subjects variable and grammaticality, hemisphere, and electrode site as within-subject variables. ANOVAs were also conducted on these measures for the implicit and explicit groups, separately. The omnibus ANOVA indicated that grammatical trials were associated with greater preresponse negativity than were ungrammatical trials, main effect of grammaticality, $F(1,22) = 6.12$, $p < .02$, but this difference was much larger for the explicit than for the implicit group, Instruction x Grammaticality interaction, $F(1,22)$, $p < .01$, especially over frontocentral sites, Instruction Set x Grammaticality x Location interaction, $F(1,22) = 4.53$, $p < .016$. Specifically, the explicit group showed significantly greater preresponse negativity for grammatical than ungrammatical trials, main effect of grammaticality $F(1,11) = 14.29$, $p < .003$; Grammaticality x Electrode interaction $F(5,55) = 5.24$, $p < .016$, $e = 0.30$. They also showed less postresponse positivity for grammatical relative to ungrammatical trials, main effect of grammaticality $F(1,11) = 9.14$, $p < .01$, that was slightly larger over the left central site, Grammaticality x Electrode interaction, $F(5,55) = 3.17$, $p < .06$, $e = 0.31$; Grammaticality x Hemisphere x Electrode interaction, $F(5,55) = 2.53$, $p < .07$, $e = 0.56$. The implicit group showed no significant effects of grammaticality within either latency window.

The overlap-corrected stimulus-locked ERPs displayed a broad positive-going component, peaking about 350 ms post-stimulus, which was more positive for grammatical trials than ungrammatical trials (Figure 12). The ERPs for each subject were quantified by mean amplitude measurements within the

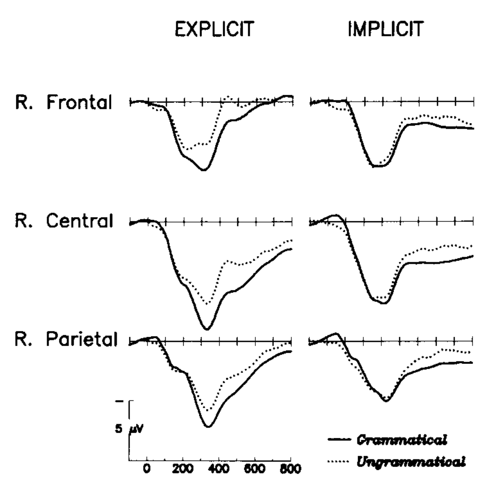

Figure 12. Grand average overlap-corrected stimulus-locked ERPs elicited by grammatical and ungrammatical target motions under implicit and explicit conditions in Experiment 2 (right hemisphere sites).

200-500-ms latency window, relative to a 100-ms prestimulus baseline and subjected to a 2 x 2 x 2 x 6 ANOVA with repeated measures using instruction set as a between-subjects variable and grammaticality, hemisphere, and electrode site as within-subject variables. A main effect of grammaticality reflected the larger positivity for grammatical than for ungrammatical trials, $F(1,22) = 16.32$, $p < .0005$. Although right hemisphere potentials were overall more positive than those at left hemisphere sites, main effect of hemisphere, $F(1,22) = 15.31$, $p < .0007$, hemisphere was involved in a significant three-way interaction with instruction set and grammaticality, $F(1,22) = 5.22$, $p < .03$ (Figure 13), because of the presence of greater right hemisphere positivity for grammatical trials in the explicit group. The implicit group also showed significantly greater positivity for grammatical trials, main effect of grammaticality, $F(1,11) = 5.55$, $p < .05$, but the effect was smaller, with later onset (approximately 300 vs. 200 ms), and was more broadly distributed spatially and temporally (no Grammaticality x Hemisphere or Electrode Site interaction) than for the explicit group.

Discussion

In this experiment the instruction set manipulation led to a robust difference in reportable knowledge between participants in the explicit (96.76%) and implicit (28.08%) groups on the prediction questionnaire. Of course, this result is silent as to whether the explicit group participants actually performed the task in an explicit manner or merely recalled the grammar during the postexperiment debriefing. But the RT performance of the explicit participants was enhanced relative to that of implicit participants, indicating that they were successfully applying their knowledge on line.

Participants under both implicit and explicit conditions showed a large RT facilitation of grammatical trials relative to ungrammatical trials even in the first half-hour of practice, probably because of the simplicity of the grammar (a repeating loop). Moreover, RTs from both groups were sensitive to the fine-grain associative structure among the four motion types, which was independent of probability of occurrence.

As in Experiment 1, (a) the target motions elicited larger P300 components than standard motions and (b) the P300 had a much longer latency on ungrammatical than on grammatical trials, consistent with the object making an unexpected movement. The P300 was slightly enhanced under explicit conditions regardless of grammaticality.

The relative difference between ERPs elicited by grammatical and ungrammatical standards revealed a small positivity to ungrammatical trials between 250 and 350 ms, which appears to reflect a kind of *expected target* effect. Ungrammatical standards consist of two subtypes: those where a target was expected (+ET) and those where another standard was expected (-ET). For the targets, grammaticality and target expectation are completely confounded. Figure 14 shows that the enhanced positivity to ungrammatical standards is due entirely to the +ET trials. This finding is consistent with P300 behavior in general; the lack of a target when one is expected elicits a robust P300. In the present design, however, these trials are not task relevant, so the effect is much attenuated.

The relative difference between ERPs elicited by grammatical and ungrammatical targets revealed greater positivity between 200 and 500 ms, slightly larger for the explicit than for the implicit group. The spatial distribution of both effects was very similar to that observed for the grammaticality effect in Experiment 1.

The primary research question of this experiment was whether violations of explicit conceptually driven expectancy would elicit qualitatively different ERPs from those elicited by violations of putatively implicit expectancy. The corrected data show some evidence of differential processing under explicit and implicit conditions. In the response-locked averages, grammatical trials under explicit conditions elicited significantly greater preresponse negativity (the *readiness potential;* for reviews, see Hillyard, 1973; Tecce, 1972) over frontal electrode sites and a larger motor potential over site C3 (located approximately over motor cortex, contralateral to the responding hand) to ungrammatical trials. In the corrected stimulus-locked averages, a significantly larger P300 was elicited under explicit conditions, regardless of grammaticality. Second, the overlap corrected data suggest an alternate interpretation of the ERP

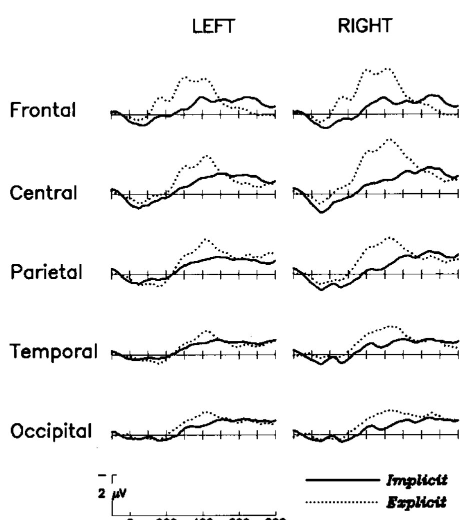

Figure 13. Difference waves produced by subtracting the overlap-corrected stimulus-locked ERPs elicited by grammatical target motions from the ungrammatical target motions under implicit and explicit instructions in Experiment 2.

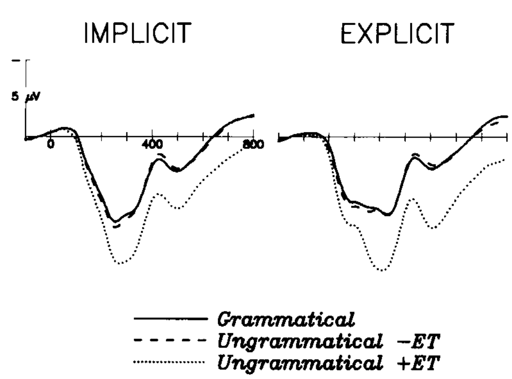

Figure 14. The grand average ERPs elicited by grammatical standards and by ungrammatical standards subdivided by whether or not they replaced an expected target motion (+ET/-ET), under implicit and explicit instructions (Experiment 2; site = Cz).

grammaticality effect. Under implicit conditions, this effect virtually disappeared in both the corrected stimulus- and response-locked averages, although small temporally dispersed effects remained. This finding indicates that most of the original effect was not due to the addition of a negativity in the 300-600-ms latency range but rather to a delay in latency for the response-locked motor positivity on ungrammatical trials, possibly because of differences in subcortical processing not easily imaged in the scalp-recorded EEG (e.g., differences in processing in the basal ganglia and/or cerebellum). Under explicit conditions, however, an apparent negative component remained, although more frontally distributed and more lateralized over the right hemisphere than had been previously observed. This finding suggests qualitatively different processing of sequential expectancy under implicit and explicit conditions and hence separable underlying mechanisms.

GENERAL DISCUSSION

There were two research goals in this study. The first was to isolate the ERP correlates of performance in an ISSL task. An increasing facilitation of the RTs on grammatical trials relative to ungrammatical trials as a function of practice indicated that participants learned something about the sequential structure, despite displaying little awareness of that structure on a post-experiment explicit prediction test. The pattern of ERPs likewise showed that participants developed expectancies about upcoming events, because when these expectancies were violated, the ERPs differed. Specifically, the ERP reflected the ungrammaticality of an event within 200 ms of its occurrence, albeit differently for standard and target stimuli; for standard stimuli, ungrammatical ERPs were more positive between 250 and 350 ms, whereas for targets ungrammatical trials were more negative in this interval and beyond. This ERP effect on targets peaked around 400 ms, was largest over centroparietal scalp locations, and emerged with practice. This ERP target effect also interacted with decision difficulty; it was largest for the most difficult motion discriminations. These effects were replicated in a second experiment. Both data sets revealed that the apparent negativity is largely due to a delayed positivity (P3) to the ungrammatical targets. The effect virtually disappears when RTs for grammatical and ungrammatical trials are matched and when response-related activity is removed from stimulus-locked averages after overlap correction.

The second research goal was to use the isolated ERP correlate of ISSL as a dependent measure to address the issue of the commonality of the neural mechanisms underlying this type of sequence learning without anything but the input versus knowledge of the rule describing the sequence. Overall, the ERPs elicited by a violation of putatively implicit expectancy in Experiments 1 and 2 and by a violation of explicit expectancy in Experiment 2 were more similar to each other than they were different. Thus, the results are more in line with idea that implicit and explicit learning involve similar brain mechanisms; the presence of a similar late positivity in both cases, albeit slightly larger in the explicit condition suggests that the magnitude of a late positivity may reflect varying amounts of concomitant awareness. This late positivity appeared to be a delayed P300 to the ungrammatical targets, which occur in unexpected locations. This component is known to be sensitive to conscious awareness, including manipulations of attention and decision confidence (for review, see Hillyard & Picton, 1987). Thus, this component is smaller under the implicit than under the explicit conditions but is otherwise similar.

In Experiment 2, the underlying grammar was simplified to the point that it could be easily taught to participants prior to the experiment. Thus, we were able to directly compare implicit and explicit learning for the same sequences. Because one obvious difference between implicit and explicit conditions was the overall faster RTs in the explicit condition, we applied an overlap-correction filter to tease apart the ERP effects related to stimulus processing and those related primarily to response processing. Overall, the grammaticality effect time locked to the processing of the stimulus under the two learning conditions was quite similar, although it was larger and more peaked and started almost 150 ms earlier under explicit instructions. Whether these differences indicate only greater synchrony under explicit instructions rather than a qualitatively different process being called into play remains an open question, although the different spatial distributions of the effects do hint at differential processing under the two conditions. The grammaticality effect in the stimulus-locked data do show greater activity over right frontocentral sites under explicit than under implicit instructions (because of greater positivity for grammatical trials).

The right frontal activity under explicit conditions is consistent with the recent demonstration by Grafton, Hazeltine, and Ivry (1994) using the positron emission tomography methodology that cerebral blood flow during motor sequence learning was increased in right prefrontal cortex when individuals became aware of a repeating pattern. Similarly, explicit stem-completion with words from previously studied lists is associated with changes in blood flow in prefrontal cortical regions, especially on the right (Squire et al., 1992).

The response-locked activity also showed that preparation for responding in the explicit conditions differed from that in implicit conditions. Only in the explicit condition was there a large grammaticality effect, with large frontal negativity prior to grammatical events. This effect is likely to reflect the more intentional ("executive") aspect of preparing to respond when the sequence is explicitly known.

Implicit learning has now been demonstrated in a variety of perceptual, motor, and cognitive tasks. Because these data probably do not reflect a unitary phenomenon, it remains unknown whether the findings reported in this paper will generalize to those paradigms.

In conclusion, learning can occur at a variety of levels in the nervous system, and there appear to be differences in the ease with which, and quite possibly in the degree to which, consciousness can penetrate those levels. For example, several studies have demonstrated preserved implicit learning in amnesic patients, including both artificial grammar learning (Knowlton, Ramus, & Squire, 1992) and structured sequence learning (Willingham et al., 1989), despite damage to their hippocampal memory system. Similarly, there are clearly a variety of different learning strategies (e.g., learning by doing, by observing, by hypothesis testing, by rote memorization) that individuals may employ, which may lead to different types of knowledge that is differentially accessible under different test conditions. Here, we have shown that although the ERP methodology can be used to contribute to our emerging understanding of the implicit learning phenomena and the deep theoretical questions they raise, the answers will be as complex as the brain from which these patterns emerge.

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