Electroencephalographic measures of attentional patterns prior to the golf putt

DEBRA J. CREWS and DANIEL M. LANDERS

Exercise and Sports Research Institute,
Arizona State University,
Tempe, AZ

ABSTRACT

CREWS, D. J. and D. M. LANDERS. Electroencephalographic measures of attentional patterns prior to the golf putt. *Med. Sci. Sports Exerc.*, Vol. 25, No. 1, pp. 116–126, 1993. The purpose of this investigation was to determine the attentional focus patterns associated with golf putting performance. Highly skilled golfers ($N = 34$) were assessed using electroencephalographic (EEG) measures of the motor and temporal cortices during the 3 s prior to the golf putt. Players completed 40, 12-ft putts and performance was measured in cm error from the hole. Three measures of EEG were analyzed: slow shift, 40 Hz, and relative power spectrum; representing readiness to respond, focused arousal, and general cortical activity, respectively. All three EEG measures suggested a decrease in left hemisphere, motor cortex activity as the player prepared to putt. Relative power measures also showed significant increases in right hemisphere activity in both the motor and temporal cortices. During the last second preceding the putt, increased right hemisphere alpha activity correlated with and predicted less error. Hemispheric differentiation was also reduced as subjects prepared to putt and few, but important, differences existed between the motor and temporal cortices. An important distinction occurred in the alpha band. In the motor cortex left hemisphere alpha increased significantly over time while in the temporal cortex, right hemisphere alpha increased as subjects approached stroke initiation. Differences that existed between the attentional patterns from the present study and past sport studies may relate to the use of one versus two hands to initiate the response.

ATTENTION, EEG, SLOW POTENTIAL SHIFT, 40 HZ, GOLF

Attention is defined by Tecce (31, p. 100) as a "hypothetical process of an organism which facilitates the selection of relevant stimuli from the environment (internal or external) to the exclusion of other stimuli and results in a response to the relevant stimuli." Attention is an active directional process that guides our mental activities. Thus, appropriate attentional focus in sport seems necessary to produce cognitions that lead to successful performance. Athletes, particularly in closed skill sports, recognize the importance of attentional focus and strive to develop a pattern of behaviors that facilitate the use of appropriate attentional focus strategies.

The electroencephalogram, more commonly known as EEG, is an indicator of attentive state (1). EEG measures the electrical potentials generated by nerve cells in the brain as they respond to various stimuli. Specifically, EEG occurs with the depolarization of dendritic trees of a pyramidal cell in the cerebral cortex. High test-retest EEG frequency component reliability has been reported suggesting that EEG is a stable intraindividual trait (7).

EEG has typically been used to understand psychological and physiological responses to pharmacological agents, to a variety of tasks, and to individual differences associated with processing in the brain. This measure allows researchers to learn information regarding attention and cognitions that may not be available through self-report (5), primarily because they include the study of nonconscious processes (19). With regard to sport, it is possible that EEG measures could be used to detect subtle differences between various movement activities (i.e., sport activities) and to differentiate information processing techniques of successful and unsuccessful performers during automatically produced tasks. In the past, athletes have been asked to retrospectively report their thought processes; however, as Nesbett and Wilson (17) point out, these reports are unreliable and may simply state *a priori* beliefs about their cognitive states. A behavioral technique known as the dual-task paradigm has also been used to describe the attentional characteristics of athletes prior to performance execution (16,25). Although this technique offers insight into attentional patterns, it also changes the nature of the task. Thus, the ecological validity of this technique remains questionable. The ability to use EEG as an unobtrusive indicator of attention offers researchers a means to determine attentional patterns immediately prior to and during the actual performance of many closed skill tasks. This is particularly valuable for high-skilled athletes who use an attentional mode characterized by cognitive "automation" rather than cognitive elaboration (6).

Interestingly, past research has also shown that the type of stimuli presented to the subject may differentially affect EEG in the two hemispheres of the brain. For example, in right-handed subjects the right hemi-

0195-9131/93/2501-0116$3.00/0
MEDICINE AND SCIENCE IN SPORTS AND EXERCISE

Submitted for publication September 1991.
Accepted for publication July 1992.

sphere is activated during spatial and musical tasks, while the left hemisphere is more active during verbal and mathematical tasks (1). Hemispheric asymmetry has been tested using several EEG analysis techniques. Three of these techniques, which may be applicable to sport, will be discussed relative to hemispheric asymmetry.

EEG Power Frequency

Power spectrum analysis of the EEG signal is the measure of continuous brain activity, which has been reported in the previous sport studies (10,14,15,26). This analysis technique uses a Fast Fourier Transform algorithm to decompose the electrical signal into its frequency components. The amplitude of each designated frequency is measured and the plot of power (amplitude) versus frequency is the power spectrum of the signal. This measure may be expressed as absolute or relative power. Absolute power represents the mean power in each frequency band selected while relative power represents the relationship between the power in the selected frequency bands compared with the total power (i.e., percentage of total power represented by each frequency band). The four frequency band divisions (i.e., theta, alpha, beta, and beta II) are responsive to specific types of stimuli and thus represent different aspects of cognitive processing. Changes in power in the specific frequency bands of the EEG may also vary at specific sites in the brain that are known to be associated with the task. For example, emotional tasks are more likely to produce increased activation (i.e., beta activity) in the frontal lobes of the brain, while motor tasks stimulate the central brain regions.

Alpha (8–12 Hz) and beta (13–20 Hz) activity have been studied extensively, while theta and beta II activity are less well understood. Alpha is present in an awake and relaxed condition. Ray and Cole (20) have suggested that alpha represents an attentive state and beta activity represents emotional involvement in the task. Beta would be present in a condition of tactile, auditory, or emotional stimulation, and in a state of tension or anxiety. Beta II activity (21–30 Hz) has not been clearly defined as representing cognitive processes different from beta activity. However, this frequency range tends to be active in schizophrenics and high anxious performers (18).

It is believed that theta (4–7 Hz) represents a "scanning for pleasure." Theta is likely to exist in an inactive processing condition in which excitatory processes are inhibited, or in an overlearned behavioral condition, similar to an automatic processing state in sport. It is apparent that each of the four grouped frequency bands represent a different psychological state for the athlete and it would be of interest to determine the contribution of each frequency band as one prepares to perform a movement.

Hemispheric asymmetry of continuous EEG has also been identified during sport activity. Hatfield et al. (10) examined hemispheric asymmetry among elite marksmen. As shooters prepared to fire a rifle there was a shift from predominantly left to right hemispheric activation, similar to the hemispheric asymmetry observed when these same subjects solved a mathematical problem. In fact, the differences between the left and right temporal hemispheres of the brain were greater during shooting than during problem solving. These same hemispheric patterns have also been observed among elite archers (26) and indicate that the left hemisphere becomes less active as the athlete approaches release. In addition, Landers et al. (14) found that beginning archers developed EEG hemispheric asymmetry patterns after they improved archery performance 62% in a 16-wk beginning archery class.

In addition to examining continuous EEG patterns, there are two other EEG signals that provide unique information of cognitive processes that may be relevant to sport. Slow potential shift is a measure of "readiness to respond" and 40 Hz activity measures "focused arousal."

Slow Shift EEG

Slow shift EEG was originally labeled contingent negative variation (CNV) and refers to a shift in the baseline component of the EEG signal as one prepares to respond. A warning and imperative signal are necessary to measure the CNV. However, the Bereitschaftspotential (BSP), or readiness potential, is a slow potential shift that is recorded approximately 1 s preceding voluntary movement situations (4,13). No warning signal is required to produce this response. The magnitude of this slow shift measure is associated with greater readiness to respond. In the present study, the BP signal will be measured since no warning stimulus will be given to the subjects.

Using biofeedback (2), Landers et al. (15) have shown that archery performance was enhanced following the training of a left hemisphere shift. Archers who were able to increase the magnitude of the BSP shift in the left hemisphere, improved performance on a 27-trial shooting task. In contrast, increased BSP shift in the right hemisphere produced a decrement in performance on the shooting task. Unfortunately, the amount of slow shift during actual shooting performance was not measured in this study.

Both of these slow potential shift signals have shown hemispheric asymmetry to relevant stimuli. Rohrbaugh et al. (24) and Syndulko and Lindsley (30) found larger CNV amplitudes from the hemisphere contralateral to the moving hand in a simple reaction time (RT) task. Kornhuber and Deecke (13) also found hemispheric differences in the BSP signal, which was related to hand preference. Interestingly, Brunia (3) found larger CNVs in the hemisphere contralateral to the finger used in a RT task, yet found larger CNVs in the hemisphere ipsilateral to a right foot RT task.

40-Hz EEG

A measure of cortical activity known as 40-Hz EEG may be very applicable to sport activity. Laboratory tasks, such as RT and mental arithmetic, have typically been collected under relatively low levels of arousal (29). However, 40-Hz EEG is labeled as a measure of "focused arousal" (27).

Sheer (27) describes this frequency band of activity (36–44 Hz) as "coherent resonance at an optimal periodicity." This essentially means that when cortical activity at a specific sensory site is increased and stimuli are presented to that sensory system, subassemblies of cells fire in synchrony at approximately 40 $\text{cycles}\cdot\text{s}^{-1}$. Furthermore, Sheer differentiates 40-Hz EEG from general arousal, suggesting that it represents a very specific sensory response.

Sheer (27) and his students have shown that: (a) 40-Hz EEG can be measured from various cortical sites, (b) hemispheric asymmetry can be detected with 40-Hz measures, and (c) 40-Hz EEG can be trained (increased and decreased) using biofeedback techniques.

This measure appears to be an appropriate measure for the sport environment. Alpha and beta activity are gross measures of generalized cortical activation in various areas of the brain, while 40-Hz EEG indicates a higher degree of specialization to various brain regions involved in the task (27). These regions have been prepared by general activation, which may be facilitated in the sport environment, for specific sensory input. For example, in sport it is likely that the motor cortex would represent the specific brain region that receives increased phasic excitation due to the arousing stimulation of the event.

The three EEG measures that have been described relate to varying components of attention. The power spectrum describes an increase or decrease in general activation at the sites examined. Slow potential shift represents "readiness" to respond and 40-Hz EEG describes a state of "focused arousal." These three EEG measures of attentional focus have not been collected simultaneously during a movement activity. Thus far, only continuous EEG has been examined during actual sport performance.

The previous sport studies used continuous EEG from the temporal region of the brain to examine attentional patterns of archers (14,15) and rifle shooters (10) in sports that require some degree of physical exertion. Although it has been shown (26) that attentional influences supercede the physical demands of the task when using power spectrum analysis, it was desirable in this study to employ an activity with no physical exertion and to include an EEG measure from the motor cortex. Golf putting was the skill selected to adequately measure continuous EEG, slow potential shift, and 40-Hz EEG.

The purpose of this study was, first, to confirm the existence of hemispheric asymmetry patterns in the motor and temporal cortices, using continuous EEG, during preparation for the golf putt. Second, this study was designed to examine the patterns of slow potential shift and 40-Hz EEG in the right and left hemispheres of the motor cortex, prior to initiation of the putting stroke. Last, it was of interest to compare the relationship of all three measures of brain activity (i.e., power spectrum, slow potential shift, and 40-Hz EEG) with performance.

The three hypotheses examined in this study are as follows. First, it was hypothesized that continuous EEG in the temporal cortex would show a reduction in left hemisphere activity and no change in the right hemisphere as initiation of the stroke approached. Motor cortex activity has not been examined in sport; therefore, no directional hypotheses were determined for this site. Second, it was hypothesized that slow potential shift would be present in the left hemisphere, and that 40-Hz activity in the left hemisphere would decrease as initiation of the stroke approached. Last, it was hypothesized that the three measures of EEG would all be related to putting performance; however, at this time there is not ample research comparing the three measures with performance to hypothesize which would be the best predictor of putting skill.

METHODS

Subjects

Right-handed, highly skilled male (N = 17) and female (N = 17) golfers (average handicap = 3.64) volunteered to participate in this study and provided informed consent. One-half of the subjects were amateur players while the other half were golf-teaching professionals. The average age of the subjects was 29.5 yr (males, $M = 31.0$; females, $M = 28.0$) and the average years of golfing experience was 15.9 years (males, $M = 16.06$; females, $M = 15.8$).

Performance Measure

Each putt was measured as cm error from the hole. Due to size limitations of the indoor putting green, the maximum error possible was 61 cm, measured from the closest rim of the hole.

Physiological Measures

A Beckman Dynograph was used to amplify four measures of raw EEG and a Biolab System amplified the electrocardiogram (ECG) and respiration activity measures for each subject. ECG rate and respiration results from this study have been reported in another paper. A Kikusui Digital Storage Oscilloscope was used to record electro-oculogram (EOG). The amplifier was connected to an RC Electronics analog-to-digital data collection board. An RC Electronics Mass Data Acquisition software program was used to collect the four channels of data. The data were stored in a large capacity hard drive, transfered to VHS tape (Alphamicro), and finally to a mainframe computer tape for subsequent data analysis.

EEG measures. The sampling rate for all data was 250 samples$\cdot$s^{-1}. In an attempt to replicate earlier data collection with shooters and archers (10,14,15,26), EEG was collected from T_3 and T_4 (processing of verbal and spatial orientation) and compared with measures of electrical activity directly over the motor cortex, 1 cm anterior to C_3 and C_4. These sites were in accord with the International 10–20 System (11) and the temporal site was chosen based on greater hemispheric differentiation during sport activity than found at parietal and occipital sites (10).

The high and low frequency filters were set at 0.01 and 100 Hz. The signals were amplified by a factor of 100,000 and the time constant was measured to be 10 s. Beckman 3-mm Ag-AgCl electrodes were attached at each of the four EEG sites. A reference electrode was placed on the right and left mastoid, and a ground electrode was placed on the left earlobe. Each site was cleaned with alcohol and Omni Prep abrasive cleaner. EC-2 electrode cream was used as the conductant material from the surface of the scalp to the EEG electrode. All impedance was measured with a Grass Instruments Electrode Impedance Meter Model (EZM5A) to attain a measure below 5K ohms. EEG electrodes were joined to a junction box and connected to the Dynograph amplifier.

EOG measures. EOG was recorded using 3 mm Ag-AgCl electrodes that were placed on the lateral canthus and the superior orbital ridge on the right eye. Preparation for electrode placement was identical to EEG electrode placement except that impedance was below 10K ohms. This measure was recorded to control for EEG artifact due to eye movement and blinks. The signal was monitored on the oscilloscope and any trial containing EOG artifact was repeated. Less than 1% of the total 1,360 trials were repeated.

Stroke Initiation

A photoelectronic device (Telemecanique XUG-J04313) was used to send a marker to one channel in the data acquisition system indicating the initiation of the putting stroke. The device was positioned so a beam of light passed perpendicular to the putting line, directly behind the putter head. As the putter began its motion backward, the shaft of the putter broke the beam of light and sent the marker to one channel of the data storage system. All data analysis was performed in reference to this mark, representing the initiation of the stroke.

Procedures

Upon arrival at the laboratory, a written informed consent approved by the Institutional Committee on the Use of Human Subjects was signed by all subjects preceding a 30-min rest during which electrodes were attached. The quality of all signals was monitored and subjects were given time to familiarize themselves with the putting surface. Data were collected for 8 s during each of the 40 putts for each condition.

Data Reduction

EEG data from four sites (T_3, T_4, C_3, C_4) were copied two times and, with the use of three software programs,[1] the data were averaged over the 40 trials.

EEG power frequency. To replicate previous research (26), the power spectrum analysis program (Run Technologies) provided relative power measures for each 1 s epoch prior to initiation of the stroke. The frequency bands were grouped into four ranges that consisted of theta (5–7 Hz), alpha (8–12 Hz), beta (13–20 Hz), and beta II (21–31 Hz).

Slow shift EEG. To examine slow potential shift, a software program[1] was written according to the specifications of Rockstroh et al. (22). Preceding stroke initiation, the average amplitude EEG measure during Epoch 3 was subtracted from the average amplitude during Epoch 2 and Epoch 1. The average shift for Epoch 2 and for Epoch 1 was combined for the 40 trials.

40-Hz EEG. Last, a software program[1] was written according to the specifications of Sheer (27) to measure 40-Hz EEG (36–44 Hz band). First, the raw EEG signal was filtered at 20–90 Hz. The filtered signal was then duplicated and one copy was filtered at 36–44 Hz. The second copy was filtered at 62–78 Hz. Each 40-Hz signal lasting a minimum of 50 ms at 2-μV amplitude, which was not coincident with 70-Hz EEG (representing EMG artifact), was counted as a burst of 40-Hz activity. The number of bursts was totaled during each 1 s epoch prior to the stroke.

Design and Analysis

Factorial multivariate analysis of variance (MANOVA) and univariate analysis of variance (ANOVA)

---

[1] The computer software programs written to analyze the slow shift and 40 Hz EEG may be obtained from the first author upon written request.

statistics were used to determine significant changes over time in the motor and temporal cortices. Significant results ($P < 0.05$) were followed by Tukey *post-hoc* comparisons. The Greenhouse-Geisser (8) correction factor was applied to all univariate statistical analyses to control for a Type I error. The reported degrees of freedom are the ϵ - adjusted degrees of freedom. Pearson product-moment correlation examined the relationship between the three EEG measures and performance.

RESULTS

Hypothesis 1

The first hypothesis suggested that for continuous EEG in the motor and temporal cortices, there would be a reduction in left hemisphere activity and no change in the right hemisphere as subjects approached stroke initiation. To test this hypothesis a 2 × 3 (hemisphere × time) factorial design was used and a hemisphere × time interaction was predicted. In support of hypothesis 1, the MANOVA main effect and interaction for theta, alpha, beta, and beta II and the individual ANOVA interactions in the motor cortex were all significant (see Table 1). Nearly identical results occurred in the temporal cortex (see Table 2). The data in the temporal cortex included a significant hemispheric main effect for beta activity and did not show the significant hemisphere × time interaction for beta II activity that was found in the motor cortex.

Tukey *post-hoc* analyses for the motor cortex ANOVAs confirmed that the left hemisphere showed significant changes over time indicated by increased alpha activity, decreased beta activity, and no change in beta II activity compared with the right hemisphere. Tukey *post-hoc* analyses also revealed that the right hemisphere showed no change over time for alpha and beta activity in the motor cortex. However, the right hemisphere showed a significant ($P < 0.001$) decrease in theta activity and an increase in beta II activity from epoch 3 to epoch 1. The raw data values are presented in Table 3 and the interaction effects are displayed in Figure 1.

TABLE 1. Significant motor cortex results for slow shift, 40-Hz, and relative power EEG.

EEG Measure	Analysis	*F*-Value	*df*
Slow shift	Hem × Time	9.90*	1.00, 33.00
40 Hz	Time	16.74***	1.84, 60.82
	Hem × Time	15.68***	1.83, 60.31
Relative Power	MANOVA		
	Hem	13.94***	2.71, 20.35
	Time	10.29***	3.47, 54.63
	Hem × Time	13.49***	3.00, 47.26
Relative Power	ANOVAs		
Theta	Time	9.96***	1.80, 59.24
	Hem × Time	7.79**	1.89, 30.28
Alpha	Hem	4.98*	1.00, 33.00
	Hem × Time	9.13***	1.79, 58.99
Beta	Time	5.56**	1.56, 51.31
	Hem × Time	9.68***	1.99, 65.69
Beta II	Time	6.37*	1.59, 52.41
	Hem × Time	4.22*	1.81, 59.70

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

TABLE 2. Significant temporal cortex results for relative power EEG

EEG Measure	Analysis	*F*-Value	*df*
Relative power	MANOVA		
	Hem	9.22***	4.00, 30.00
	Time	3.38*	3.34, 52.67
	Hem × Time	6.61***	2.38, 37.52
Relative power	ANOVAs		
Theta	Time	9.40***	1.69, 55.90
	Hem × Time	12.68***	1.88, 62.01
Alpha	Hem	5.40*	1.00, 33.00
	Hem × Time	4.78*	1.63, 53.87
Beta	Hem	8.47**	1.00, 33.00
	Time	3.61*	1.61, 53.00
	Hem × Time	12.87***	1.99, 62.65
Beta II	Time	8.71***	1.69, 55.80

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

The temporal cortex showed similar results to the motor cortex (see Fig. 2). *Post-hoc* analysis revealed that results were the same in the theta and beta bands for the temporal cortex as found in the motor cortex. However, alpha band results were opposite in the temporal cortex. *Right* hemisphere alpha power decreased significantly ($P < 0.05$) over time in the temporal cortex; while in the motor cortex, *left* hemisphere alpha increased significantly ($P < 0.05$) from epoch 3 to epoch 1. Temporal cortex, beta II activity increased similarly in both hemispheres ($P < 0.05$), as opposed to a significant right hemisphere increase in the motor cortex.

Figures 3 and 4 illustrate the motor and temporal

TABLE 3. Raw data values for the motor and temporal cortices.

		Epoch 3	Epoch 2	Epoch 1
Motor Cortex				
Slow shift	R	−3.81 ± 2.27	2.98 ± 21.84	7.31 ± 21.00
	L	−0.79 ± 2.17	3.01 ± 18.12	−5.59 ± 18.73
40 Hz	R	15.88 ± 3.70	15.62 ± 3.73	15.89 ± 4.06
	L	17.09 ± 4.57	16.56 ± 4.46	15.40 ± 4.55
Theta	R	1.49 ± 0.66	1.50 ± 0.67	1.11 ± 0.55
	L	1.27 ± 0.51	1.36 ± 0.57	1.25 ± 0.47
Alpha	R	1.16 ± 0.20	1.17 ± 0.19	1.14 ± 0.19
	L	1.03 ± 0.20	1.05 ± 0.23	1.13 ± 0.22
Beta	R	1.09 ± 0.24	1.08 ± 0.20	1.10 ± 0.22
	L	1.25 ± 0.24	1.18 ± 0.26	1.07 ± 0.12
Beta II	R	0.71 ± 0.23	0.71 ± 0.22	0.83 ± 0.21
	L	0.77 ± 0.17	0.77 ± 0.19	0.81 ± 0.25
Temporal Cortex				
Theta	R	1.36 ± 0.64	1.39 ± 0.68	0.91 ± 0.65
	L	1.04 ± 0.52	1.14 ± 0.60	1.06 ± 0.65
Alpha	R	1.04 ± 0.25	1.05 ± 0.22	0.96 ± 0.23
	L	0.93 ± 0.24	0.93 ± 0.23	0.95 ± 0.30
Beta	R	1.11 ± 0.22	1.09 ± 0.21	1.14 ± 0.20
	L	1.29 ± 0.24	1.23 ± 0.26	1.12 ± 0.16
Beta II	R	0.83 ± 0.31	0.82 ± 0.28	1.01 ± 0.31
	L	0.90 ± 0.24	0.89 ± 0.25	0.98 ± 0.34

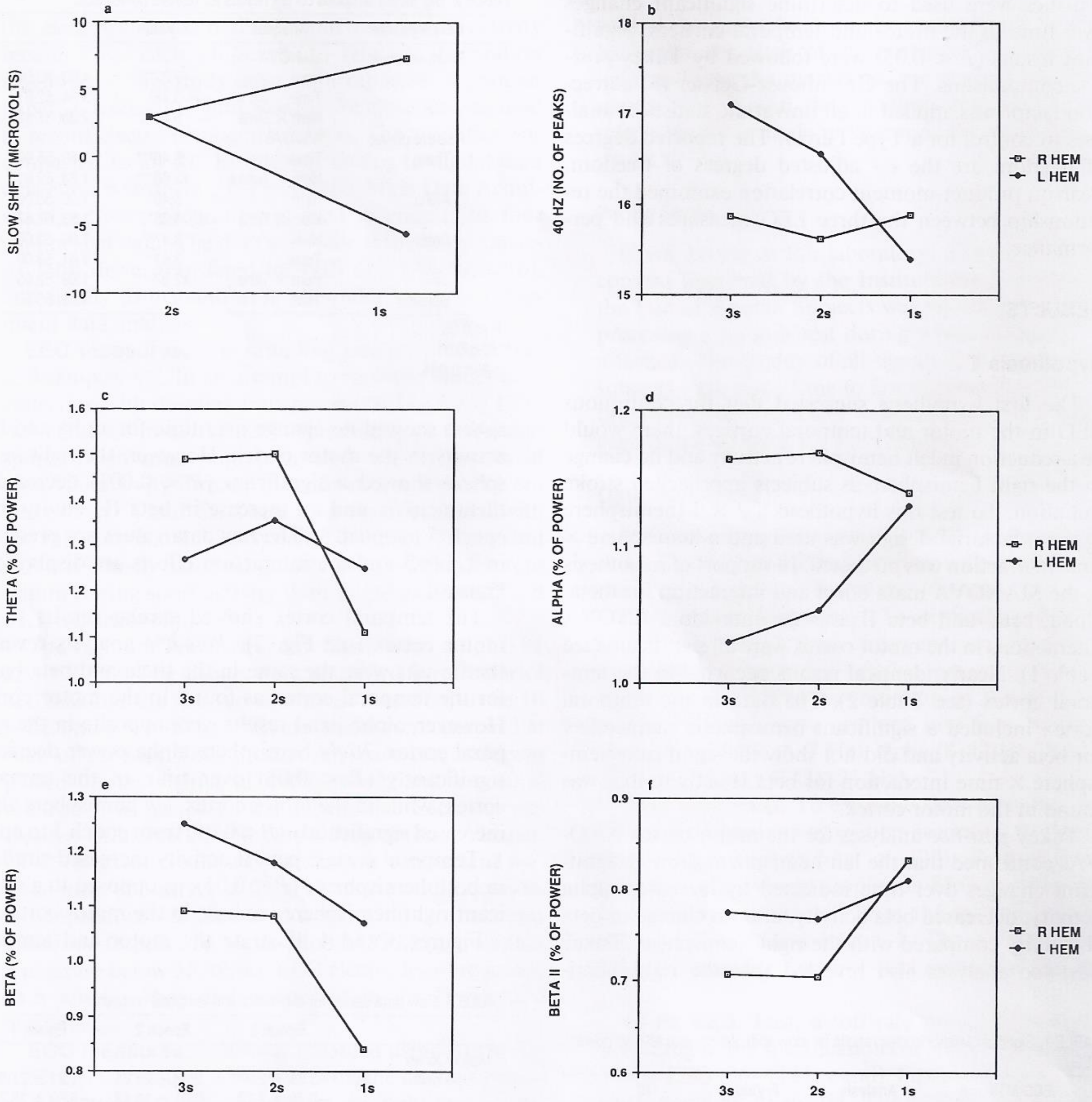

Figure 1—(a) Slow shift, (b) 40 Hz EEG, and relative power for (c) theta, (d) alpha, (e) beta, (f) beta II measures for the motor cortex: epochs 3-1.

cortex hemispheric patterns separately for each epoch. It is apparent that the hemispheres became more similar in each frequency band as time to stroke initiation approached. The difference between the hemispheres was significant at epoch 3 and 2 and was nonsignificant at epoch 1.

Hypothesis 2

The second hypothesis suggested that slow potential shift would be greater and 40-Hz EEG would be less in the left compared with the right hemisphere prior to golf putting performance. The 2 × 3 (hemisphere × time) interactions that support this hypothesis were significant (see Table 1). As seen in Figure 1 (a), slow potential shift in the left hemisphere (motor cortex) showed a significant ($P < 0.01$) negative shift from epoch 2 to epoch 1. (Epoch 3 served as a baseline and was subtracted from Epochs 2 and 1.) Although the right hemisphere displayed a positive shift from epoch 2 to epoch 1, this was not significant. Also seen in Figure 1 (b), left hemisphere 40 Hz significantly ($P < .001$) decreased in the number of 40-Hz peaks from epoch 3 to epoch 1 and from epoch 2 to epoch 1. Raw

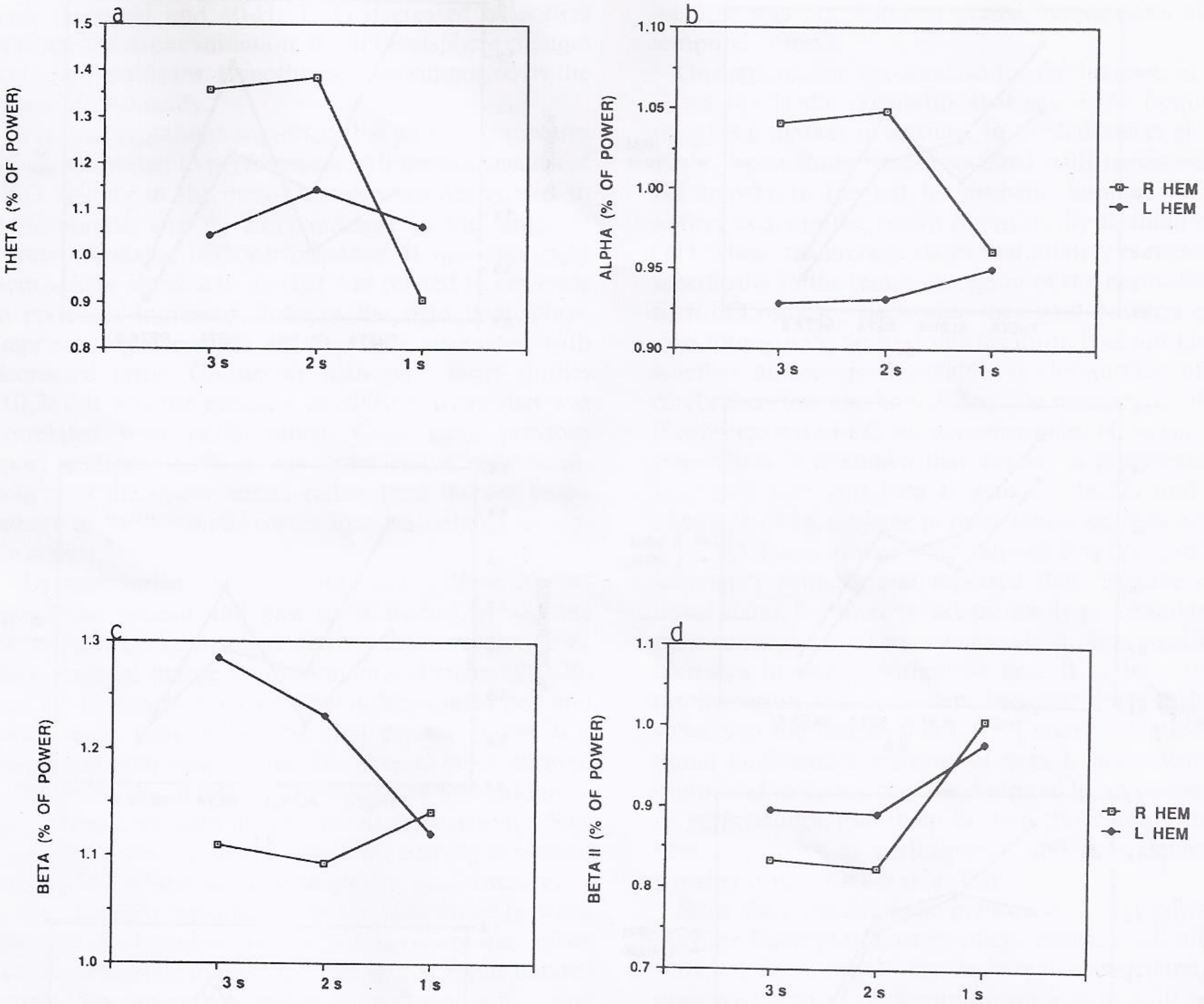

Figure 2—Relative power for (a) theta, (b) alpha, (c) beta, (d) beta II measures for the temporal cortex: epochs 3-1.

data values for these two signals are presented in Table 3.

Hypothesis 3

According to the last hypothesis, all EEG measures would be correlated with performance. Based on previous research (26), significant correlations of EEG activity to performance would be most likely to occur at epoch 1. Therefore, to control for alpha inflation when examining slow shift, 40-Hz activity, and relative power measures in the right and left hemispheres of the motor cortex and relative power measures only for the temporal cortex, correlations were only performed for epoch 1 EEG measures with cm error. In addition, the alpha level was reduced by the total number of correlations ($N = 20$) in the right and left hemispheres of the motor and temporal cortices ($0.05/20$, $P < 0.002$). One significant correlation existed from the motor cortex at Epoch 1 comparing right hemisphere alpha activity with cm error ($r = -0.51$, $P = 0.001$). At 1 s before the putt, the best performing subjects displayed more alpha activity, and right hemisphere alpha power accounted for approximately 25% of the variance in performance. The slow shift and 40-Hz measures were not related to performance and no significant correlations with performance were found for the temporal cortex.

DISCUSSION

Several important similarities and differences emerged from the results of this study when compared with previous sport studies (10,14,15,26). These differences have methodological implications for future psychophysiological sport studies.

The first hypothesis implied that the continuous EEG measure would show reduced activity in the left hemisphere of the temporal cortex and no change in right hemisphere activity as subjects approached the putt. Theta, alpha, and beta activity all indicated reduced left hemispheric activation over time. Beta II activity

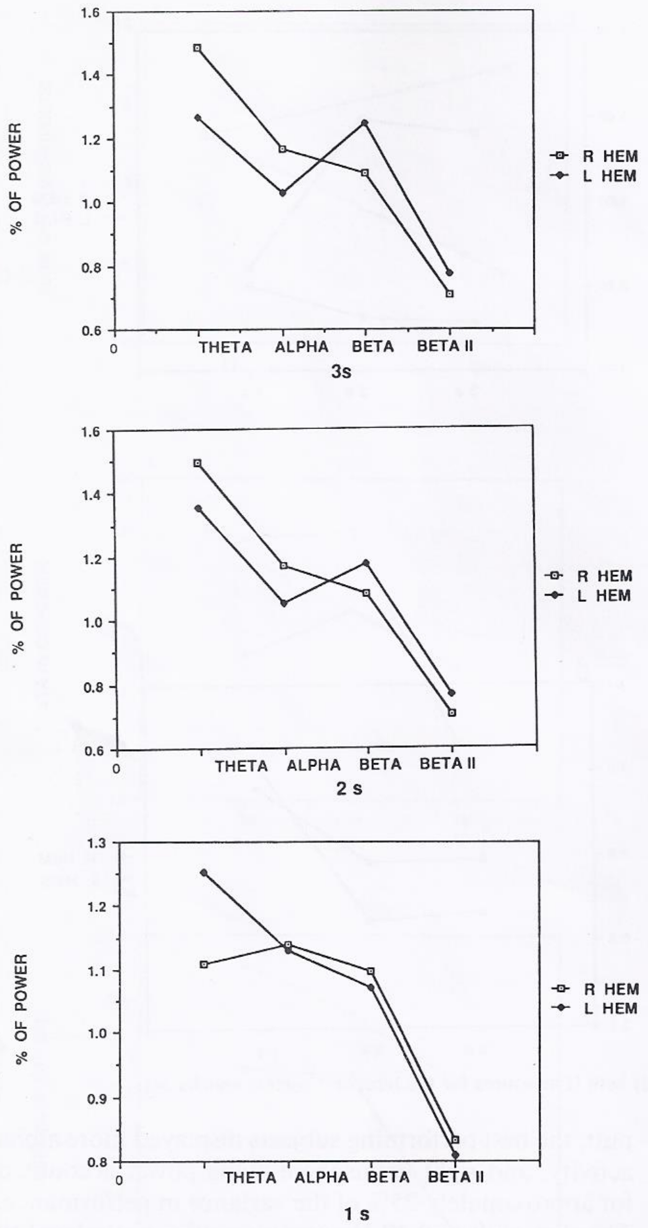

Figure 3—Hemispheric differences for the motor cortex relative power measures: epochs 3, 2, and 1. (Power measures do not total 100% due to small overlapping effects inherent in the analysis of the individual frequency bands.)

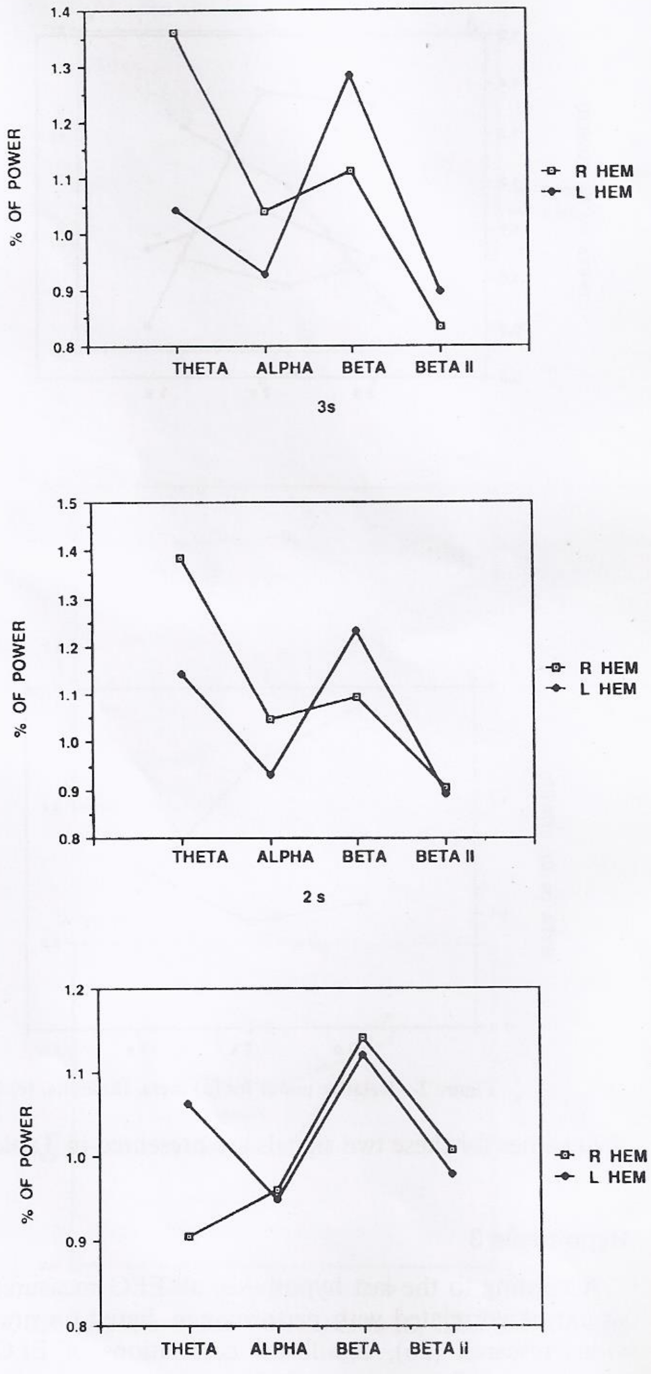

Figure 4—Hemispheric differences for the temporal cortex relative power measures: epochs 3, 2, and 1. (Power measures do not total 100% due to small overlapping effects inherent in the analysis of the individual frequency bands.)

increased similarly in both hemispheres. These results have been found in the previous sport studies (10,26); however, the right hemisphere results were inconsistent with past research (10,26). Golfers showed significantly increased right hemisphere alpha activity, when no change was hypothesized. Hypothesis 1 is partially supported by the results of this study.

Although past studies examined temporal cortex EEG, the motor cortex results were more similar to past sport studies (10,26). The left hemisphere showed reduced activation as indicated by increased alpha and reduced beta activity, and no change in theta and beta II. The right hemisphere showed no change over time for alpha and beta, yet there was decreased theta and increased beta II. The past sport study (26) that examined these frequencies showed similar left hemisphere results and a similar beta II response in the right hemisphere with no change in theta activity.

Slow shift and 40-Hz EEG were hypothesized to show change in the left hemisphere. As hypothesized, slow shift increased and 40-Hz EEG decreased as golfers approached stroke initiation. Right hemisphere changes were nonsignificant. Hypothesis 2 was supported by the results of this study.

The last hypothesis suggested that all three measures would be related to performance. All three measures of EEG activity in the motor cortex were not related to performance, and no EEG measure in the temporal cortex correlated with performance. It was only right hemisphere alpha activity that was related to cm error at epoch 1. Increased alpha in the right hemisphere (representing decreased activity) was associated with decreased error. Consistent with past sport studies (10,26), it was the measure of *alpha* activity that was correlated with performance. Contrasting previous sport studies (10,26), it was alpha in the *right* hemisphere of the *motor* cortex rather than the *left* hemisphere of the *temporal* cortex that was related to performance.

To summarize the similarities and differences between the present and past sport studies, it was the decrease in left hemisphere activity that appeared to be the consistent change for marksmen and archers (10,26) and left hemisphere activity that differentiated best and worst shots (26), indicating that greater power was associated with worst shots. The present study showed similar changes in left hemisphere alpha and, additionally, showed changes in right hemisphere activity. Surprisingly, increased right hemisphere activity explained one-quarter of the variance in putting performance.

One possible explanation for the differences between the past sport studies and the present study may relate to the mechanics involved in the sports. Right-handed marksmen and archers initiate their response by a pull of the trigger or release of the arrow with their right hand. The left hand is simply stabilizing the gun or bow. According to Brunia (3), right-handed activities are displayed as changes in the contralateral hemisphere of the brain, or in this case, the left hemisphere. This may partially explain why changes in the left hemisphere are so important for successful shooting performance. However, initiation of the putting stroke uses both hands to produce the movement and thus would not be related to a specific change in only one hemisphere. As found in this study, decreased left hemisphere activity was significant and decreased right hemisphere activity was associated with less error.

An interesting similarity existed between the present study and the Salazar et al. (26) study. They found increases in the left hemisphere of archers at 24 Hz and suggested that this finding needed replication. The present study also found significant increases in beta II activity (i.e., 21 through 31 Hz) as subjects approached stroke initiation in both the motor and temporal cortices. However, the difference was significant in the right hemisphere only, of the motor cortex and the increase was not different across hemispheres in the temporal cortex.

One speculative explanation for the increase in beta II activity is the possibility that this EEG frequency signal is a marker of anxiety. In the Salazar et al. (26) study, worst shots were associated with increased 28-Hz activity in the left hemisphere. Support for this notion exists in the recent discovery by Reiman et al. (21). These researchers claim that anxiety is measured specifically in the temporal region of the brain. Rather than EEG surface electrodes, they used positron emission tomography to find this location. It is not known whether anxiety is detectable at the surface of the cerebral cortex, nor how diffuse the measure would be if collected with EEG surface electrodes. However, past researchers have shown that anxiety is represented as increased beta and beta II activity (18,28) and that highly anxious subjects portray increased beta activation (12). Furthermore, Harman and Ray (9) examined laboratory subjects and reported that negative emotional states, like anxiety, are primarily processed in the right hemisphere. The present study showed significant increases in right hemisphere beta II activity in the motor cortex and equivalent increases in both hemispheres in the temporal cortex. A study using bidirectional biofeedback training of beta II activity in the motor and temporal cortices, followed by an assessment of performance may help explain the relationship of beta II activity to performance and may determine whether it is a marker of anxiety.

Slow shift results of the present study partially support the findings of past research. Biofeedback of slow shift activity in the left hemisphere was associated with improved archery performance while slow shift in the right hemisphere produced performance decrements (15). In the present study, the left hemisphere shift increased from epoch 2 to epoch 1; however, there was no relationship with cm error.

Hemispheric differentiation of 40 Hz activity has not been previously examined in sport. However, in nonsport performance it is apparent that hemispheric differences relate to motor responses. Spydell and Sheer (29) found decreased alpha and beta II activity and increased left hemisphere 40-Hz activity when subjects performed a problem solving task. Using two conditions in which subjects searched for computerized targets, one involving automatic processing and the other requiring effortful processing, Rogers (23) found a decrease in percent error during the automatic processing condition that was concomitant with a reduction in left hemisphere 40-Hz activity. Athletes continually strive for a state of "automatic processing" and the results of the present study showed that putting preparation induced a reduction in left hemisphere activity similar to Roger's laboratory task.

Slow shift and 40-Hz EEG require further investigation during sport activities. Both appear to show hemispheric differentiation during the golf putt. However, only alpha activity has shown a consistent relationship with sport performance. These two measures may show a relationship with performance in a competitive environment as opposed to a "practice" setting.

In conclusion, hypothesis 1, stating that continuous EEG would show a reduction in left hemisphere activity with no change in the right hemisphere, was partially supported by the results of this study. All three measures demonstrated reductions in left hemisphere activity; however, relative power measures also showed increases in right hemisphere activity in both the motor and temporal cortices. Hypothesis 2, stating that left hemisphere slow shift would increase and 40-Hz activity would decrease during attentional preparation, was supported in this golf putting task. Last, hypothesis 3, suggesting that all three measures of EEG would be related to putting performance, was not supported by the results of this study. It was only right hemisphere alpha that was related to performance error. Interestingly, Landers et al. (14) showed that novice archers develop hemispheric differentiation as they learned the sport and this study showed that skilled performers reduce hemispheric differentiation as subjects *approached* stroke initiation. The important distinction between the motor and temporal cortices showed that in the motor cortex there was an increase in *left* hemisphere alpha power, while in the temporal cortex *right* hemisphere alpha decreased significantly from epoch 3 to epoch 1. Although some of these EEG differences appear to be small, the effect sizes representing the change in power from either epoch 3 or epoch 2 to epoch 1 ranged from 0.00 to 3.39 with an average effect size of 0.51. Thus, these appear to be meaningful, statistically significant changes over time and in level of activation.

Future research examining additional brain sites may shed light on the predominant patterns for each hemisphere and on the sites specific to the task. Biofeedback of these three EEG signals may validate and explain their relationship with sport performance. An examination of golfers who use the long putter, which like archery/shooting requires stabilization by one hand and stroke execution with the other hand, may help to determine if one- versus two-handed activities explain the differences in the right hemisphere found between this study and previous sport studies (10,14,15,26).

The authors wish to express their appreciation to Walter Salazar and Steven Petruzzello for their comments on earlier drafts of this manuscript.

Address for correspondence: Debra J. Crews, Ph.D., University of North Carolina — Greensboro, Department of Exercise and Sport Science, Greensboro, NC 27412-5001.

REFERENCES

1. ANDREASSI, J. L. *Psychophysiology.* New York: Oxford, 1980, p. 100.
2. BIRBAUMER, N., T. ELBERT, B. ROCKSTROH, and W. LUTZENBERGER. Biofeedback of event-related potentials of the brain. *Int. J. Psychol.* 16:389–415, 1981.
3. BRUNIA, C. H. M. What is wrong with legs in motor preparation. In: *Motivation, Motor and Sensory Processes of the Brain, Prog. Brain Res.*, H. H. Kornhuber and L. Deecke (Eds.). Elsevier/North-Holland: Biomedical, 54: 1980.
4. DEECKE, L. and H. H. KORNHUBER. An electrical sign of participation of the mesial "supplementary" motor cortex in human voluntary finger movement. *Brain Res.*, 159:437–476, 1978.
5. DEMENT, W. *Some Must Watch While Others Must Sleep.* San Francisco: Freeman, 1974.
6. FITTS, P. M. and M. I. POSNER. *Human Performance.* Belmont, CA: Brooks/Cole, 1967.
7. GASSER, T., P. BACHER, and H. STEINBERG. Test-retest reliability of spectral parameters of the EEG. *EEG Clin. Neurophysiol.* 60:312–319, 1985.
8. GREENHOUSE, S. W. and S. GEISSER. On methods in the analysis of profile data. *Psychometrika* 24:95–112, 1959.
9. HARMAN, M. W. and W. J. RAY. Hemispheric activity during affective verbal stimuli: an EEG study. *Neuropsychology* 15:457–460, 1977.
10. HATFIELD, B. D., D. M. LANDERS, and W. J. RAY. Cognitive processes during self-paced motor performance: an electroencephalographic profile of skilled marksmen. *J. Sport Exerc. Psychol.* 6:42–59, 1984.
11. JASPER, H. H. Report of the committee on methods of clinical examination in electroencephalography. *EEG Clin. Neurophysiol.* 10:370–375, 1958.
12. KENNARD, M. A. Effects on EEG of chronic lesions of basal ganglia, thalamus and hypothalamus of monkeys. *J. Neurophysiol.* 6:405–416, 1943.
13. KORNHUBER, H. H. and L. DEECKE. Motivation, motor and sensory processes of the brain. Electrical potentials, behavior and clinical use. *Prog. Brain Res.* Amsterdam, Elsevier, 54: 1980.
14. LANDERS, D. M., M. W. HAN, W. SALAZAR, S. J. PETRUZZELLO, and K. KUBITZ. Electroencephalographic (EEG) patterns of novice archers, *Int. J. Sport Psychol.* in press.
15. LANDERS, D. M., S. J. PETRUZZELLO, W. SALAZAR, et al. The influence of electrocortical biofeedback on performance in pre-elite archers. *Med. Sci. Sports Exerc.* 23:123–129, 1991.
16. LANDERS, D. M., M. Q. WANG, and P. COURTET. Peripheral narrowing among experienced and inexperienced rifle shooters under low- and high-stress conditions. *Res. Q. Exerc. Sport.* 56:122–130, 1985.
17. NESBETT, R. E. and T. D. WILSON. Telling more than we can know: verbal reports on mental processes. *Psychol. Rev.* 84:231–259, 1977.
18. NIEDERMEYER, E. and F. LOPES DA SILVA. *Electroencephalography.* Baltimore: Urban and Schwarzenburg, 1983, pp. 71–91.
19. RAY, W. The electrocortical system. In: *Principles of Psychophysiology: Physical, Social and Inferential Elements*, J. T. Cacioppo and L. G. Tassinary (Eds.). New York: Cambridge, 1990, 385–412.
20. RAY, W. J. and H. C. COLE. EEG alpha activity reflects attentional demands and beta activity reflects emotional and cognitive processes. *Science* 228:750–752, 1985.
21. REIMAN, E. M., M. J. FUSSELMAN, P. T. FOX, and M. E. RAICHLE. Neuroanatomical correlates of anticipatory anxiety. *Science* 243:1071–1072, 1989.
22. ROCKSTROH, B., T. ELBERT, N. BIRBAUMER, and W. LUTZENBERGER. *Slow Brain Potentials and Behavior.* Baltimore: Urban and Schwarzenberg, 1982.
23. ROGERS, R. C. 40-Hz EEG Correlates of Automatic and Effortful Information Processing. Unpublished Doctoral Dissertation, University of Houston, Texas.
24. ROHRBAUGH, J. W., K. SYNDULKO, and D. B. LINDSLEY. Brain wave components of the contingent negative variation in hu-

mans. *Science* 191:1055–1057, 1976.

25. ROSE, D. J. and R. W. CHRISTINA. Attention demands of precision pistol-shooting as a function of skill level. *Res. O. Exerc. Sport* 61:111–113, 1990.
26. SALAZAR, W., D. M. LANDERS, S. J. PETRUZZELLO, D. J. CREWS, and K. A. KUBITZ. The effects of physical/cognitive load on electrocortical patterns preceding response execution in archery. *Res. O. Exerc. Sport* 61:351–359, 1990.
27. SHEER, D. E. Sensory and cognitive 40-Hz event-related potentials: behavioral correlates, brain function, and clinical application. In: *Springer Series in Brain Dynamics 2*, E. Bagar and T. H. Bullock (Eds.). Berlin: Springer-Verlag, 1989.
28. SPEHLMANN, R. *EEG Primer.* New York: Elsevier/North-Holland: Biomedical, 1981, pp. 183–199, 427–428.
29. SPYDELL, J. D. and D. E. SHEER. Effect of problem solving on right and left hemisphere 40 hertz EEG activity. *Psychophysiology* 19:420–425, 1982.
30. SYNDULKO, K. and D. B. LINDSLEY. Motor and sensory determinants of cortical slow potential shifts in man. In: *Attention, Contraction and Event Related Cerebral Potentials.* J. E. Desmedt (Ed.). Basel: Karger, 1977, pp. 97–131.
31. TECCE, J. J. Contingent negative variation (CNV) and psychological processes in man. *Psychol. Bull.* 77:73–108, 1972.