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# Cortico-cortical Communication and Superior Performance in Skilled Marksmen: An EEG Coherence Analysis

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Electroencephalographic (EEG) coherence was assessed during a 4-s aiming period prior to trigger pull in expert marksmen (*n* = 10) and skilled shooters (*n* = 9) over the course of a regulation round of small-bore rifle shooting. Although both groups were highly experienced, the skilled group had lower ability. Given that specialization of cortical function occurs as domain-specific expertise increases, experts were predicted to exhibit less cortico-cortical communication, especially between cognitive and motor areas, compared to the skilled group. Coherence was assessed for three frequency bands (low alpha, 8–10 Hz; high alpha, 10–13 Hz; and low beta, 13–22 Hz) using sites F3, Fz, F4, C3, Cz, C4, T3, T4, P3, Pz, P4, O1, and O2. Compared to the skilled group, experts exhibited lower coherence between left temporal (T3) and midline frontal (Fz) regions for low-alpha and low-beta frequencies, lower coherence for high-alpha between all left hemisphere sites and (Fz), and lower coherence between T3 and all midline sites for the low-beta band. The results reveal that, compared to lesser skilled shooters, experts engage in less cortico-cortical communication, particularly between left temporal association and motor control regions, which implies decreased involvement of cognition with motor processes.

Key Words: expert performance, marksmanship, psychophysiology

Optimal athletic performance is typically characterized by biomechanical and metabolic efficiency (Sparrow, 1983, 2000). Hatfield and Hillman (2001) have suggested that highly skilled performance is also associated with greater efficiency in that expert performers use more appropriate cortical processing than do less skilled performers to accomplish a given task. This results in higher quality (i.e., economical) and more consistent motor output.

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Fitts and Posner (1967) proposed three phases of motor skill learning and described the earliest, the cognitive stage, as being characterized by effortful processing of perceptual cues and conscious regulation of movement. The associative, or middle, stage is characterized by refinement of sensory processing of relevant stimuli and more efficient timing and execution of movements. The final stage of skill development, the autonomous stage, is one during which automaticity prevails over conscious regulation of movement. These ideas have been refined in cognitive and sport psychology over the past few decades in related conceptual frameworks (e.g., Bargh & Chartrand, 1999; Kimble, 2000; Logan, 1988; Schneider & Shiffrin, 1977), but the basic tenet of Fitts and Posner concerning the attainment of automaticity remains widely accepted. Therefore, as individuals become more skilled, one would predict that the strategies employed during the planning and execution of a movement would become automatized and that cognitive analysis would be associated with lower levels of skill (Deikman, 1969; Klatzky, 1984; Langer & Imber, 1979; Masters, 1992, 2000).

To address this issue, the present study subscribed to a psychophysiological approach and examined functional communication between different areas of the cerebral cortex in two groups of experienced shooters who differed in skill level. Because the left temporal region has been shown to be active during cognitive analysis, while decreasing in activation during the performance of visuospatial tasks (Smith, McEvoy, & Gevins, 1999; Springer & Deutsch, 1998), particular interest was focused on the relationship between the left temporal region and the motor planning areas of the cortex.

The electroencephalogram (EEG) has proven to be a useful tool for examining psychological states during skilled motor performance (Lawton, Hung, Saarela, & Hatfield, 1998). The EEG captures fluctuations of electrical voltage in the cortex through electrodes placed on the scalp in accordance with the standardized guidelines of the International 10–20 system (Jasper, 1958). Due to the high temporal resolution of EEG, the fluctuating voltage related to cognition, attention, and arousal can be measured on the order of ms, providing a dynamic measure of such processes. The contribution of component frequencies to the resultant EEG voltage time series expressed as power ($\mu V^2$), such as the alpha (8–13 Hz) band, can be assessed in different regions or spatial locations of the cortex and related to cortical activation. Because the different regions relate to specific mental functions, topographical assessment of EEG can be employed to infer psychological processes. For a more detailed review of EEG methodology and its application to sport psychology, see Lawton et al. (1998) and Hatfield and Hillman (2001).

Previous studies have revealed that superior marksmanship is associated with increasing alpha power in the left temporal region across successive epochs leading to the initiation of the shot (Hatfield, Landers, & Ray, 1984), as well as higher levels in expert marksmen compared to novice shooters (Haufler, Spalding, Santa Maria, & Hatfield, 2000). Intervention studies have also revealed that target shooting practice and the associated improvement in performance is associated with increased levels of left temporal alpha power (Kerick, 2001; Landers, Han, Salazar, et al., 1994). By incorporating appropriate control conditions in marksmen, Kerick, McDowell, Hung, et al. (2001) and Salazar, Landers, Petruzzello, et al. (1990) provided evidence that synchrony of left temporal alpha power prior to shot execution is indeed related to task-relevant cognitive processes rather than being a simple reflection of lower-order motor processes.

Loze, Collins, and Holmes (2001) also reported heightened alpha power with better shooting accuracy in a group of elite pistol shooters. However, the relationship may not be linear, as Salazar et al. (1990) observed poorer performance in skilled archers when accompanied by the highest observed levels of alpha and low-beta spectral power in the left hemisphere prior to arrow release. Additionally, Hillman, Apparies, Janelle, and Hatfield (2000) observed heightened-alpha and low-beta power in both the left and right hemispheres of the cerebral cortex in marksmen during the aiming period before shots rejected when compared to shots executed. The rejection of a shot refers to withdrawal from the target during the aiming period due to a lack of optimal attention and engagement with the task.

Collectively, the EEG studies of target shooting demonstrate the importance of cortical activation in the left temporal area to performance and suggest a relationship that appears to be characterized by an inverted-U. Lower levels of alpha power in the left temporal area may reflect cognitive analysis of the task, moderate levels may imply reduction of such processes, and excessively high alpha power may indicate an inability to optimally engage with the task. Taken together, these studies provide robust evidence that left temporal lobe activity is associated with target shooting performance.

Skillful target shooting also requires involvement of regions of the brain that are responsible for visual-spatial processing, planning and control of movement, and the efficient integration or orchestration of these processes. Although previous studies of cortical processes during target shooting have employed event-related slow potentials (Konttinen & Lyytinen, 1992, 1993) and EEG power spectral analysis (Hatfield et al., 1984; Haufler et al., 2000; Hillman et al., 2000; Landers et al., 1994; Salazar et al., 1990), such measurement techniques have not allowed for examination of the functional communication between different areas of the brain (e.g., cognitive and motor). EEG coherence analysis can be used to addresses the issue of functional communication in the cortex and may help to more accurately describe the state of optimal attentional focus needed to perform at an elite level.

Coherence is a frequency-dependent measure of the degree of linear relatedness between time series simultaneously recorded from two locations. Coherence values indicate the magnitude of correlation between the respective amplitudes derived for a given frequency (or band) from the two time series. High EEG coherence implies communication between different areas of the cerebral cortex while low coherence is indicative of regional autonomy or independence (Nunez, 1995). Lower coherence between visuospatial, language, and motor areas of the cortex would be expected as specialization increases, functional communication between the involved areas decreases, and motor skill becomes more refined. Indeed, researchers have observed decreases in coherence following learning (Busk & Galbraith, 1975) or development (Bell & Fox, 1996) of motor skill.

Decreased coherence during the aiming period of a shooting task would indicate regionally-specific activation, allowing motor areas of the brain to execute the task with relative independence and with less influence from verbal or analytical processing. In this manner, more efficient cortical organization may result in high quality and consistent performance by reducing the complexity of motor processes.

In a classic study, Busk and Galbraith (1975) employed coherence analysis after recording continuous EEG from four electrode sites (Fz, C3, C4, Oz) to examine changes in cortical communication during the learning of an eye-hand tracking task. They observed a significant decrease in coherence between all coupled electrode sites following one practice session consisting of 20 trials, with the greatest decrease between the electrodes located over the premotor (Fz) and motor cortices (C3, C4). Busk and Galbraith suggested that the decrease in coherence was consistent with an interpretation of increased efficiency of cortical processes and decreased task difficulty due to learning. However, this measure has not been examined in highly skilled individuals who have practiced a motor task over many years. Additionally, Busk and Galbraith did not include electrodes over cognitive association areas of the brain, such as the left temporal lobe (T3), in their design.

Although a number of researchers have employed coherence analysis to examine functional communication in the cortex during verbal tasks (Razoumnikova, 2000; Sheppard & Boyer, 1990; Volf & Razumnikova, 1999) and various other cognitive and creative tasks (Petsche, 1996; Petsche, Kaplan, von Stein, & Filz, 1997), we are aware of no published reports of the interaction between cognitive and motor areas during the execution of psychomotor skill in individuals who are highly skilled.

The current study focused on coherence between two main areas of the cortex: One areas was the premotor (Fz), which is instrumental in the planning of movement and has direct cortical connections to the motor cortex, the visual cortex, and the association areas in the temporal and parietal lobes (Kaufer & Lewis, 1999). The other region of interest was the left temporal (T3) which, as stated above, has been implicated in target shooting performance and has known projections to motor areas of the cortex (Kaufer & Lewis, 1999). Additionally, Nunez (1995) has suggested that alpha (8–13 Hz) and low-beta (13–22 Hz) frequencies reflect global cortico-cortical communication, while higher frequency bandwidths (e.g., 36–44 Hz) are more indicative of regional processing, or more localized activation of the cortex.

Some researchers have also noted specificity in the alpha band and recommended that the lower (8–10 Hz) and higher (10–13 Hz) components should be examined separately (Klimesch, 1999; Petsche et al., 1997; Smith et al., 1999). The lower component (8–10 Hz) appears to be sensitive to changes in general arousal (Smith et al., 1999; for a review see Klimesch, 1999), while the higher frequency component (10–13 Hz) is more indicative of task-specific attentional processes (Smith et al., 1999). Accordingly, coherence analysis in the present study was applied separately to the low-alpha (8–10 Hz), high-alpha (10–13 Hz), and low-beta (13–22 Hz) frequency bands in light of their sensitivity to more global cortico-cortical communication.

Therefore the purpose of the present study was to examine whether skill level was negatively related to alpha- and beta-band EEG coherence between known cognitive and motor planning areas of the cortex. For two groups of highly practiced shooters, who were observed during the aiming period of rifle shooting, experts were predicted to exhibit lower coherence estimates than a skilled group (i.e., of lower ability) for high-alpha and low-beta frequencies in light of the sensitivity of these bands to task-specific attention demands. No group difference was predicted for low-alpha coherence since both groups of participants were presumed to engage similarly with the task demands. Since it was assumed that experts would engage in less cognitive analysis and self-talk than the skilled group during the aiming period, the difference in coherence was predicted to be most pronounced between the left hemisphere, especially the left temporal region (T3), and the motor planning area (Fz). Rather than examine coherence between all possible electrode pairs, the design focused on coherence from a number of cortical sites to the premotor region and to the left temporal region, with primary emphasis on the connection between these areas.

## Method

### *Participants*

The participants included 10 expert (9 M, 1 F) and 9 skilled (7 M, 2 F) marksmen. The experts ranged in age from 16 to 62 years (*M* = 40.8, *SD* = 15.0), and the skilled participants ranged from 13 to 62 years of age (*M* = 35.6 ± 18.8). Although number of years of shooting experience was similar for the experts (*M* = 17.9 ± 14.1) and the skilled participants (*M* = 19.7 ± 21.4), the experts had significantly more years of competitive experience (*M* = 14.3 ± 12.9) than the other group (*M* = 5.4 ± 13.1). Participants were grouped objectively according to the National Rifle Association's international competition classification,[1] and formal classification was supplemented by the assessment of a professional coach who was a former world-class competitor and Olympic gold medalist. In this manner the participants were further distinguished based on their performance history, such that the experts had consistently performed at a higher level under practice and match conditions. All participants shot right-handed, although one expert reported being left-hand dominant. All participants were ipsilateral-eye dominant except for one expert and one skilled shooter, who were both left-eye dominant.

### *Procedures*

After being informed about the general purpose of the study, all participants were asked to read and sign an informed consent form which had been approved by the institutional review board. They were then given the opportunity to ask questions about the experiment. The participants were individually tested in a soundproof room where they were required to stand 5 m from the small-bore rifle target that measured 10 mm in diameter, a proportionally sized target that allowed them to maintain the official distance of 50 feet from the target.

After dressing in regulation shooting attire, participants were fitted with a Lycra electrode cap. Omni-prep and Electrode Cap International (ECI) electrode gel were then applied to 13 electrode sites (F3, Fz, F4, T3, C3, Cz, C4, T4, P3, Pz, P4, O1, O2) corresponding to the International 10–20 system (Jasper, 1958). Forty shots were executed during an 80-min period in accordance with official rules of competition at national and international levels. The participants shot in the standing position and were allowed to rest the rifle on a post in between shots. They were also allowed to sit briefly after each block of 10 shots. The details of the shooting task are described elsewhere (Haufler et al., 2000).

### *Instrumentation*

*Shooting Simulator*. The Noptel Shooter Training System (ST-2000, version 2.33) was used to measure shooting performance. The system consists of a light-emitting and receiving unit capable of measuring shot accuracy and time on target without employing live ammunition.

*EEG.* EEG data were collected and amplified 50,000 times using Grass model 12A5 Neurodata Acquisition amplifiers with a band-pass filter setting of 0.1–100 Hz and a 60-Hz notch filter. Analog data were collected continuously at a rate of 512 samples/sec using a Metrabyte analog/digital converter and were recorded on-line with Neuroscan Scan 4.03 software installed on a Gateway 2000 Pentium computer. Vertical and horizontal eye movement artifact were measured through the use of bipolar electro-oculographic activity (EOG) in which vertical EOG was assessed by electrodes placed above and below the right eye while horizontal EOG was assessed by electrodes located at the outer canthi. Impedance values for all electrode sites were maintained below 5kΩ.

All sites were initially referenced to A1 and re-referenced offline to an average ears reference (A1, A2). A frontal midline site (FPz) served as the ground. EEG was subjected offline to an eye-correction algorithm (Semlitsch, Anderer, Schuster, & Presslich, 1986) to transform the time series and remove ocular artifact. A small microphone mounted on the barrel of the rifle detected the sound of the hammer of the rifle and marked the EEG trace, thus indicating the execution of the shot. The data were then subjected to a low-pass filter set at 35 Hz (35 dB/octave rolloff). Four 1-s epochs were generated prior to the event marker with the end of the last epoch synchronous with the event marker. The data were baseline-corrected and any epoch containing amplitude excursions in excess of 75 ± μV was excluded.

EEG coherence was calculated using Neuroscan 4.1.1 software on the electrode pairings of interest. Coherence was defined as $|C_{xy}(f)|^2$, where:

$$C_{xy}(f) = \frac{\sum_i \{X_i(f) - \bar{X}(f)\}\,\{Y_i(f) - \bar{Y}(f)\}^*}{\sqrt{\sum_i |X_i(f) - \bar{X}(f)|^2 \sum_i |Y_i(f) - \bar{Y}(f)|^2}}$$

and where $X_i(f)$ and $Y_i(f)$ represent the Fourier transforms of the time series for electrode sites $X$ and $Y$, respectively. Coherence was calculated in 1-Hz frequency bins and averaged across the appropriate frequencies to obtain the coherence values for the bandwidths of interest (8–10 Hz, 10–13 Hz, and 13–22 Hz). All coherence values were subjected to a Fisher z-transformation prior to analysis to ensure normal distribution.

## *Design*

Each of the bands (low-alpha, 8–10 Hz; high-alpha, 10–13 Hz; low-beta, 13–22 Hz) was subjected, separately, to two multivariate analyses of variance (MANOVA) procedures. The first design delineated coherence between bilateral regions of the brain and a midline frontal electrode site (Fz) over the premotor region. Coherence estimates between the Fz electrode and all bilateral active electrode sites in the five regions (see Figure 1a) were subjected to a 2 × 5 × 2 × 4 (Group × Region × Hemisphere × Epoch) MANOVA with repeated measures on region, hemisphere, and epoch. The groups were designated expert and skilled. Region referred to the electrode placement in five regions of the brain: frontal, central, temporal, parietal, and occipital. Hemisphere contained two levels and referred to the electrodes overlying the left and right hemisphere regions of the scalp, respectively (i.e., no midline sites). Epoch referred to the 4-s aiming period,

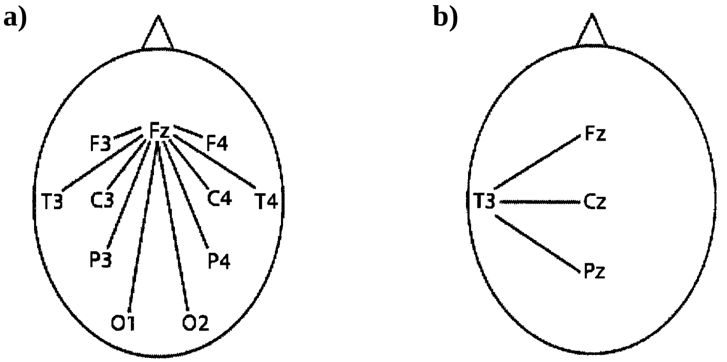

**Figure 1 — (a) Left and right hemisphere electrode sites paired with site Fz (premotor area); (b) Midline electrode sites paired with site T3 (left temporal lobe).**

which was divided into four 1-s epochs prior to shot execution. The analysis was designed to examine hemispheric and regional differences in communication with the premotor area between experts and skilled shooters over time.

The second design was used to examine coherence between the left temporal lobe area (T3) and three midline electrode sites: Fz, Cz, and Pz (see Figure 1b). Coherence estimates for each band were subjected to separate 2 × 3 × 4 (Group × Midline Site × Epoch) MANOVAs with repeated measures on the last two factors. Group and epoch factors were the same as above; there was no hemisphere factor. This analysis allowed for the examination of group differences in communication between the left temporal lobe area and the frontal (premotor area), central (motor cortex), and parietal regions over time.

Because specific predictions regarding the groups were confined to T3–Fz coherence, a *t*-test was conducted on this electrode pairing to determine significance in the event of a significant omnibus test, $p < .05$. All other mean comparisons were conducted using Tukey HSD when appropriate.

Spectral power ($\mu V^2$) within each of the specified bandwidths at each electrode position was also examined to determine whether activation of the cortex differed between groups. Spectral power was subjected separately to the 2 × 5 × 2 × 4 (Group × Region × Hemisphere × Epoch) and the 2 × 3 × 4 (Group ×Midline Site × Epoch) designs described above. All analyses were conducted using SPSS version 10.0.

## Results

### Performance

The mean score for the expert participants was 7.78 ($SD$ = 0.80) out of a possible 10. The mean score for the skilled group was significantly lower at 3.84 (±1.65), $t(17) = 6.75$, $p \leq 0.001$. The expert shooters also spent more time on target during the aiming period ($M$ = 13.86 s ± 4.19) compared to skilled shooters ($M$ = 8.10 s ± 2.93), $t(17) = 3.44$, $p = 0.003$.

## *EEG*

All statistical analyses were based on the Fisher z-transformation of the coherence values. All means reported in the text and figures are the original or raw coherence estimates. Epoch was included as a factor in the original design, due to the observed changes in spectral power across the epochs of the aiming period in previous research (Hatfield et al., 1984). However, no main effects or interactions involving epoch emerged as significant in any of the analyses.

*Low-Alpha.* The bilateral design (2 × 5 × 2 × 4) employed to examine coherence to Fz yielded a significant Group × Region × Hemisphere interaction, $F(4, 14) = 5.55$, $p = 0.007$, as illustrated in Figure 2. Post-hoc tests revealed that expert shooters (.236) exhibited significantly lower coherence values than the skilled group (.341) at the T3–Fz electrode pairing and did not differ significantly from the skilled shooters at any other electrode paring. The three-way interaction was accompanied by a significant Group × Hemisphere interaction, $F(1, 17) = 13.91$, $p = 0.002$ (see Figure 3). Post-hoc inspection of the means revealed that experts exhibited similar coherence to Fz in both hemispheres and did not differ significantly from skilled shooters in either hemisphere, while the skilled shooters exhibited significantly higher coherence to Fz in the left hemisphere (.519) than they did in the right hemisphere (.469). This analysis also revealed a significant main effect for region, $F(4, 14) = 32.34$, $p < 0.001$, such that coherence estimates were higher in the regions closer to Fz.[2]

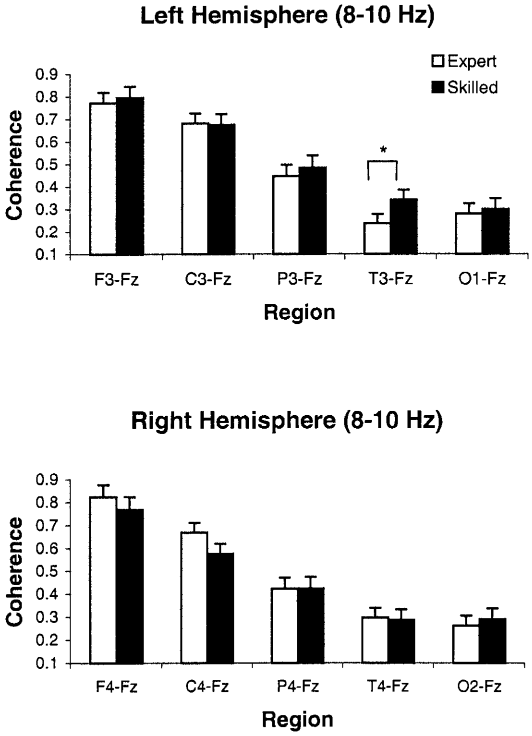

**Figure 2 — Expert and skilled group means for low-alpha (8–10 Hz) coherence estimates between Fz (premotor area) and frontal, central, temporal, parietal, and occipital sites in each cerebral hemisphere. *Significant difference, $p < .05$**

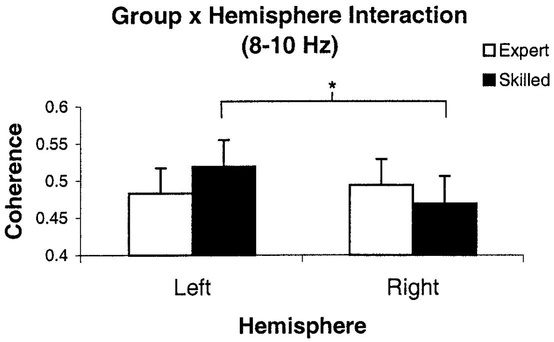

**Figure 3 — Average left- and right-hemisphere coherence estimates with Fz for expert and skilled shooters for low-alpha (8–10 Hz). *Significant difference, $p < .05$**

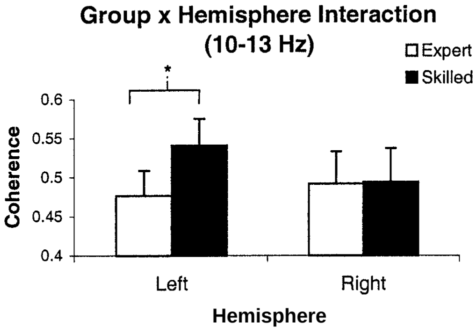

**Figure 4 — Left- and right-hemisphere coherence with Fz for expert and skilled shooters for high-alpha (10–13 Hz) frequency. *Significant difference, $p < .05$**

The 2 × 3 × 4 (Group × Midline Site × Epoch) design used to examine midline coherence with site T3 resulted in no significant main effects or interactions.

*High-Alpha.* The 2 × 5 × 2 × 4 analysis revealed a significant Group × Hemisphere interaction, $F(1, 17) = 6.06$, $p = 0.025$ (Figure 4). Post-hoc tests revealed that expert shooters exhibited significantly lower coherence (.477) than did skilled shooters (.541) in left hemisphere coherence to Fz, while no such difference occurred in the right hemisphere. The Group × Region × Hemisphere interaction approached significance, $F(4, 14) = 2.88$, $p = 0.062$, such that the pattern of mean differences observed between groups was similar to that evident in the corresponding three-way interaction reported for low-alpha coherence.

*Low-Beta.* The 2 × 5 × 2 × 4 analysis revealed a significant Group × Region × Hemisphere interaction, $F(4, 14) = 6.06$, $p = 0.006$ (see Figure 5). Post-hoc testing revealed that experts exhibited significantly lower coherence than the skilled group at the T3–Fz electrode pairing (.182 and .330, respectively), but did not differ significantly from the skilled group at any other electrode pairing. Ex-

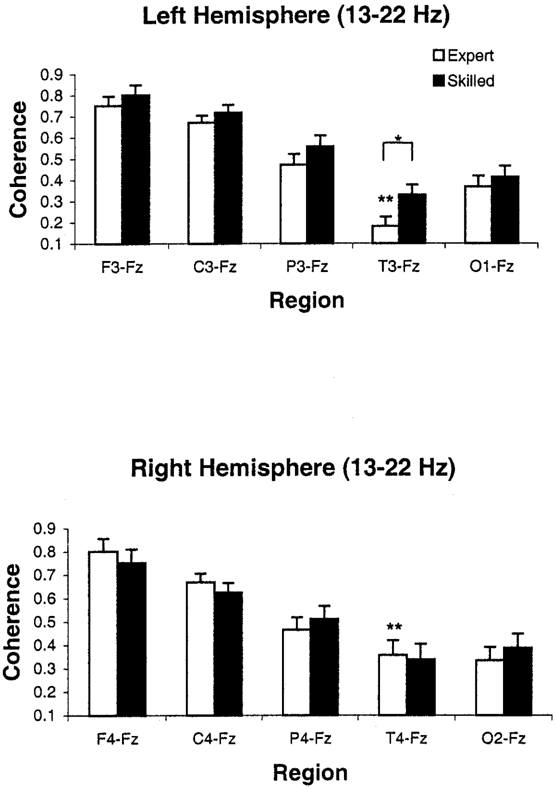

**Figure 5** — Expert and skilled group means for low-beta (13–22 Hz) coherence estimates between Fz (premotor area) and frontal, central, temporal, parietal, and occipital sites in each cerebral hemisphere. *Significant difference, $p < .05$; **T3–Fz coherence was significantly lower than T4–Fz coherence in the expert group only.

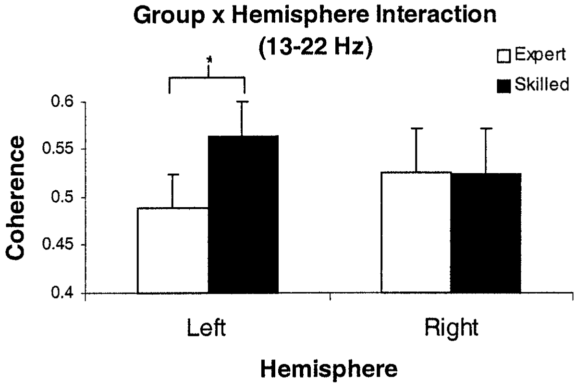

**Figure 6** — Average left- and right-hemisphere coherence estimates with Fz for expert and skilled shooters for low-beta (13–22 Hz) frequencies. *Significant difference, $p < .05$

pert shooters also exhibited significantly lower coherence at the T3–Fz electrode pairing than they did at the T4–Fz electrode pairing (.182 and .358, respectively). The three-way interaction was accompanied by a significant Group × Hemisphere interaction, $F(1, 17) = 7.54$, $p = 0.014$ (see Figure 6). Expert shooters exhibited significantly lower coherence between the left hemisphere electrodes sites and Fz, collectively, than did the skilled group (.489 and .564, respectively).

The $2 \times 3 \times 4$ analysis of coherence between T3 and the midline sites revealed a significant group effect, $F(1, 17) = 5.05$, $p = 0.038$, with a mean coherence value of .445 between T3 and the midline electrodes (Fz, Cz, Pz) for the expert group, and a mean value of .639 for the skilled group (see Figure 7).

*Spectral Power.* Spectral power analyses revealed no significant main effects or interactions in any of the frequency bands examined. These findings suggest that the overall cortical activation of experts and skilled shooters was similar.

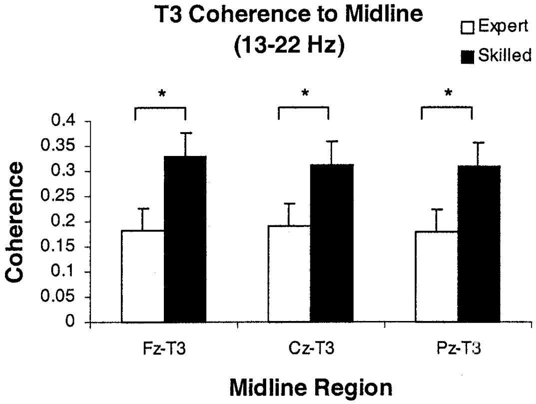

**Figure 7 — Expert and skilled group coherence estimates of low-beta (13–22 Hz) coherence for midline sites paired with T3 (left temporal lobe). *Significant difference, $p < .05$**

## Discussion

The present study examined whether expert marksmen would exhibit greater autonomy of cortical activation, as measured by EEG coherence analysis, prior to the execution of a shot, compared to a group that was highly experienced with shooting but less skilled. In general, we predicted that experts would exhibit lower coherence estimates relative to the less skilled shooters, suggesting less cortico-cortical communication during the aiming period. In regard to the specific relationship between verbal-analytic and motor processes, the predicted group difference in coherence values between the left temporal area (T3) and premotor region (Fz) was confirmed in the low-beta band, as the experts exhibited lower coherence relative to the lesser skilled shooters (Figure 5). Furthermore, the experts exhibited lower coherence between T3 and the other midline sites (Cz, Pz) for this frequency band (13–22 Hz; Figure 7). Interestingly, no significant differences emerged between groups for low-beta at any of the other sites that were paired with Fz, supporting the special relationship of coherence to expertise between the left temporal and motor regions.

The expert group also exhibited lower coherence in the high-alpha band between the midline frontal site (Fz) and all of the left hemisphere sites (Figure 4), but the predicted group difference in coherence, specifically between T3 and Fz for the high-alpha band, was in the predicted direction but only marginally significant. Although group differences in coherence were not predicted for the low-alpha bandwidth, since the 8–10 Hz band has been shown to reflect more general arousal, the experts did exhibit lower estimates for the T3–Fz electrode pairing (Figure 2). However, the difference between groups for all left hemisphere sites to Fz for the low-alpha band (Figure 3), as predicted, failed to attain significance.

Collectively, the findings suggest a decrease in communication between the left temporal lobe's association and motor planning processes in experts relative to the less skilled group. Considering the similarity in number of years of experience for both groups, the lack of statistically significant differences in some analyses is understandable, while the attainment of predicted differences in cortical functioning is remarkable. Such a finding is consistent with the notion that experts are characterized more by a state of automaticity in which cognitive elaborations would actually impede performance. In addition, the lack of group differences for coherence estimates between the right hemisphere and the premotor region seems consistent with the notion that both groups would rely similarly on functional communication between this hemisphere and the motor planning region. The right hemisphere is known to mediate visuospatial processes (Springer & Deutsch, 1998), and the integration of such processes with motor functions seems consistent with the demands of target shooting, a visual aiming task.

It is noteworthy that the experts exhibited lower coherence or functional autonomy between T3–Fz than they did for T4–Fz, as several studies have reported relative activation in the right temporal region in expert marksmen and archers (Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2001; Landers et al., 1994; Loze et al., 2001). The present findings extend the results of those previous investigations and imply that this region may be more active in order to communicate with and influence the involved motor control processes.

It is also noteworthy that the experts revealed lower coherence estimates (for low-beta) not only between T3 and Fz but also for T3 with midline central (Cz) and midline parietal (Pz). In regard to the former, the Cz region is known to index motor cortex activity so that both the planning (i.e., Fz) and execution (i.e., Cz) of cortical influences on the musculoskeletal apparatus appear to be less influenced by left hemispheric cognitive processes in persons showing higher skill levels. Furthermore, the parietal region is reported to work hand in hand with the left temporal area in order to integrate the details of stimulus feature extraction accomplished by the temporal region (Kerick, 2001). In this manner the parietal region builds a gestalt or perception of the task environment.

Lower functional communication between the left temporal and parietal regions, as observed in the experts, seems reasonable if a well-developed internal model has been established by which a strong memory representation has been formed by repeatedly negotiating the task demands. One would expect both groups in the present study to show lower coherence between these regions (T3–Pz) than novices, but it is interesting that the higher-performing experts observed herein exhibited significantly lower estimates than the skilled participants.

The lack of significant interactions or main effects with the epoch factor indicates that the functional communication processes described above were consistent or stable over the 4-s aiming period. Although the coherence estimates would not be sensitive to alterations in synchrony over time, the results obtained from the spectral analysis fail to support such an effect. Because EEG is subject to artifact, the ability to track cortical activity over a long period is limited. Therefore, it may be that brain processes during skilled marksmanship are temporally dynamic but only detectable in time frames beyond the 4- to 5-s periods as reported here and as typically reported in the literature (Haufler et al., 2000). Only Hatfield et al. (1984) reported such an effect, but their sample was composed of world-class marksmen and allowed longer durations of EEG recording during the aiming period (i.e., 7.5 s).

Because the expert and skilled participants in this study had been shooting for a similar number of years (17.9 and 19.7, respectively), a reasonable question is why some were able to achieve an expert level of performance while others were not. Ericsson, Krampe, and Tesch-Römer (1993) have suggested that expert performance does not necessarily result from years of experience. While reaching an expert level of performance may indeed take a minimum of 10 years of experience, it is also the result of prolonged deliberate practice. Deliberate practice involves activities specifically designed to improve performance. One cannot attain expert performance levels simply by engaging in the activity. Such development requires considerable effort and exploration of various strategies to improve performance. The experts in the present study may have employed different cognitive strategies over the years in deliberate attempts to improve performance, whereas the skilled shooters may have been less vigilant during practice. Such a conclusion remains speculative, however, since the participants in this study were not specifically questioned about their practice techniques and hours of practice per week.

The present findings, in addition to those of previous psychophysiological studies of motor performance, support foundational concepts in motor learning and sport psychology from an additional measurement perspective. For instance, during the earliest stage of learning it may be necessary for the learner to effortfully attend to all visual and somatosensory cues, and consciously regulate movement to perform the task (Bargh & Chartrand, 1999; Fitts & Posner, 1967; Kimble, 2000; Logan, 1988; Schneider & Shiffrin, 1977). The cortical dynamics at this stage of learning are characterized by global neural activation such that both relevant and irrelevant cortical connections are activated (Hatfield & Hillman, 2001). In this manner performance is likely to be inconsistent, as it reflects the relatively unstable neural processes. However, as skill increases, the movements become more refined, stable, and automatic.

This concept is well established in the literature on motor learning and is paralleled by research examining plastic changes in the cortex. Greenough, Black, and Wallace (1987) have suggested that with learning there is a pruning of synapses in the brain, decreasing the irrelevant connections and reinforcing the relevant ones. Busk and Galbraith (1975), employing EEG coherence, provided evidence of decreased cortico-cortical communication with the learning of a simple motor skill. Hatfield and Hillman (2001) have suggested that with increasing skill, the organization of the brain becomes more refined and subsequently more efficient, resulting in more automatic movement.

The present findings are consistent with these concepts in terms of the observed coherence between cognitive and motor planning areas in the expert performers. At advanced stages of learning, cognitive analysis is inappropriate. Augmented input from cognitive areas of the brain to motor programming may add unnecessary interference and affect the quality of the motor output (Bargh & Chartrand, 1999; Kimble, 2000; Logan, 1988; Schneider & Shiffrin, 1977). Indeed, these tendencies are characteristic of the less skilled shooters in the current study. Compared to the experts, they exhibited higher coherence between the left hemisphere and the premotor area. By contrast, expert performers' coherence levels suggested a decrease in left hemispheric communication and a suppression of the influence of analytical processing, which would allow for relatively uncomplicated execution of the task compared to the lesser skilled group.

The subjective experience of skilled athletes performing at their best has been characterized as effortless, yet there is a sense of personal control, an optimal level of attentional focus, and a general absence of cognitive analysis of the task (Williams & Krane, 1998). The findings of the present study are consistent with the predictions of the ideal performance state described by Williams and Krane if considered in light of the functions of the left hemisphere and the temporal cortex. Although the distinction between left- and right-cerebral hemispheric functioning runs the risk of oversimplification, it is accepted that the left hemisphere is associated with language comprehension and speech production (Springer & Deutsch, 1998). In addition to being associated with verbal-analytical tasks, the left temporal lobe is also involved in stimulus feature detection (Lind, Flor-Henry, & Koles, 1999).

The decrease in communication between the left temporal lobe and the premotor area in expert performers may contribute to the phenomenological experience typically reported in the form of increased focus and decreased effort or conscious thought as well as self-talk or covert verbalization. Such neurocognitive efficiency may translate into better performance characterized by economy of effort (Sparrow, 2000). In this manner the absence of cognitive analysis during peak performance may facilitate performance.

In essence, with expert motor skill the regions of the brain that are essential for performing a well-learned psychomotor task, such as the premotor area, motor cortex, and subcortical regions (basal ganglia, thalamus, and cerebellum), would be optimally engaged with little interference from areas of the cortex associated with cognitive analysis. EEG coherence cannot be used to assess cortico-subcortical communication due to limitations in spatial resolution, but advances in neuroimaging and signal processing techniques may reveal such important motor control processes in the future. Developments such as these will enable future efforts to observe the interaction of the higher cognitive regions of the brain and the predominantly motor areas in order to better understand how psychological factors influence the quality of motor performance.

## *Summary and Conclusions*

Hatfield and Hillman (2001) posited the principle of psychomotor efficiency, maintaining that expert performers require less neural activation than novices to perform a given task, and a number of researchers have provided support for this notion in terms of cortical activation measures. A preliminary report from our laboratory outlined differences in EEG coherence between expert and novice shooters, but those groups were also characterized by significant differences in cortical activation (Deeny, Haufler, & Hatfield, 2001). In the present study, the coherence measure was able to detect differences in cortico-cortical communication despite a lack of difference in cortical activation.

The similarity in cortical activation between groups seems reasonable in light of the experience that both groups had with the task. Such a finding regarding the differences in coherence, however, underscores the usefulness of this measure to resolve psychological differences associated with fine variation in skill levels. The functional communication observed between topographical regions in the cortex of the expert shooters in the present study also appears to be consistent with previous characterizations of subjective experience during superior performance. In essence, superior performers typically report an absence of conscious regulation of or "thinking" about performance. EEG coherence provides a useful measure previously absent from the sport performance literature to study such a process. The present study, by attempting to elucidate cortical communication processes that are related to performance ability, may help clarify the psychological processes or mechanisms underlying expert psychomotor performance.

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## *Notes*

[1] Cassifications are based on NRA Small-Bore Rifle Rules, revised June 1, 2001, section 19. The expert group comprised 4 sharpshooters, 5 masters, and 1 expert. The skilled group comprised 1 expert, 4 marksmen, and 4 nonclassified shooters. The expert participant assigned to the expert group had twice the competition experience as the expert participant assigned to the skilled group, and was judged by an accomplished shooting sports coach to be clearly superior. Given the potential overlap in skill level of these two individuals, the groups were also contrasted excluding them. The findings remained essentially the same with no change in the significant effects.

[2] Due to volume conduction of electrical activity in the brain, the coherence value will be artificially inflated between two proximal electrodes compared to the coherence value between two distal electrodes. Therefore, if the dependent variable is coherence to Fz, the coherence of C3 to Fz will be higher than the coherence of O1 to Fz due to the greater distance between the occipital cortex and the frontal cortex. Volume conduction should only affect the region main effect, and should not affect the interaction of region with other variables as it would be assumed constant across groups.

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