Assessment of Reactive Motor Performance With Event-Related Brain Potentials: Attention Processes in Elite Table Tennis Players

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Motor readiness, visual attention, and reaction time (RT) were assessed in 15 elite table tennis players (TTP) and 15 controls (C) during Posner’s cued attention task. Lateralized readiness potentials (LRP) were derived from contingent negative variation (CNV) at Sites C3 and C4, elicited between presentation of directional cueing (S1) and the appearance of the imperative stimulus (S2), to assess preparation for hand movement while P1 and N1 component amplitudes were derived from occipital event-related potentials (ERPs) in response to S2 to assess visual attention. Both groups had faster RT to validly cued stimuli and slower RT to invalidly cued stimuli relative to the RT to neutral stimuli that were not preceded by directional cueing, but the groups did not differ in attention benefit or cost. However, TTP did have faster RT to all imperative stimuli; they maintained superior reactivity to S2 whether preceded by valid, invalid, or neutral warning cues. Although both groups generated LRP in response to the directional cues, TTP generated larger LRP to prepare the corresponding hand for movement to the side of the cued location. TTP also had an inverse cueing effect for N1 amplitude (i.e., amplitude of N1 to the invalid cue > amplitude of N1 to the valid cue) while C visually attended to the expected and unexpected locations equally. It appears that TTP preserve superior reactivity to stimuli of uncertain location by employing a compensatory strategy to prepare their motor response to an event associated with high probability, while simultaneously devoting more visual attention to an upcoming event of lower probability.

Key Words: cognitive motor behavior, attentional flexibility, motor readiness, ERP, sport psychology

Keele and Hawkins (1982) argued that the ability to shift attention from one spatial location to another (i.e., attentional flexibility) is a critical factor in psycho-

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motor tasks that require speeded responses to environmental stimuli characterized by uncertainty of spatial location. Tennis and boxing are examples of reactive or open-skill sports that involve such psychomotor tasks. Boxers and tennis players must often execute extremely fast responses while dealing with cues or “fakes” intended to misdirect their attention. Examples are quick lateral head motions or bobs exhibited by opponents immediately prior to their returning a serve or delivering a punch. The purpose of such cues is to direct the performers’ attention to a location other than that from which the ball or punch will actually be delivered so as to slow their response. Thus it is likely that successful athletes in reactive sports are characterized by intense anticipation of stimuli and employ highly developed strategies in the visual attention and motor domains in order to respond to them effectively while dealing with any miscues and uncertainties as to spatial location.

Attentional flexibility has been examined under controlled conditions by a number of researchers using a warned choice reaction time task (an S1-S2 protocol) during which participants respond as quickly as possible to imperative stimuli that can appear in varying locations of a visual display (Posner, Nissen, & Ogden, 1978). The warning stimulus, S1, either provides information on the likely spatial location of the upcoming imperative stimulus, S2, or provides no such directional information (i.e., neutral warning cue). Further, the directional warning cues may be valid or invalid; that is, they either correctly or incorrectly indicate the location of the anticipated imperative stimuli. Participants are informed at the beginning of the protocol that the warning cues are valid for most of the trials (approx. 80%). Thus they must execute their responses quickly and accurately while being on guard for misdirection and the attendant uncertainty of stimulus location.

Using this paradigm, Posner et al. (1978) observed reaction times (RT) that were typically shorter on validly cued trials and longer on invalidly cued trials than those observed on neutral trials. Shorter RTs to validly cued stimuli reflect attention benefit while longer RTs to invalidly cued stimuli reflect attention cost (Posner, 1980). The relative magnitudes of attention benefit and cost provide a measure of attentional flexibility (Keele & Hawkins, 1982). Specifically, superior attentional flexibility of one individual (or group) relative to that of another is defined by similar or greater attention benefit accompanied by reduced cost.

Castiello and Umilta (1992) used the cued task to compare the RTs of skilled volleyball players who were experienced with reactive-sport skills to those of controls who lacked such experience; greater attentional flexibility was found in the volleyball players. The results revealed that both the volleyball players and the controls were able to capitalize on the valid directional cuing and increase the speed of their reactions relative to the neutral trials (i.e., attention benefit) in a similar manner, but the players also incurred significantly less cost (i.e., less slowing of RT) when they were miscued for stimulus location.

Such a reduction in attention cost has been observed in other groups experienced with reactive-sport activities when compared to control group participants, but typically this advantage has been accompanied by a reduction in the magnitude of attention benefit as well (Nougier, Ripoll, & Stein, 1989; Nougier, Stein, & Azemar, 1990; Nougier, Stein, & Bonnel, 1991). In this manner the athletes in the previous studies seemed specifically and primarily to guard against the influence of misdirection cues and placed a higher premium on prevention of cost than on attainment of any benefit. Based on the observed group differences in RT, it appears that athletes employ unique motor preparation and visual attention strate-
gies. However, the detection of such strategies requires that process measures be employed in addition to the behavioral level of analysis (RT).

Accordingly, electroencephalographic (EEG) measures in the form of event-related potentials (ERP) can be used to examine the neural processes underlying any differences in RT behavioral outcomes observed during Posner’s cued attention task. The constituent components of the ERP can be used to quantify the visual and motor preparation processes underlying RT (Abernethy, 2001; Spirduso, 1995). The cued task protocol allows for examination of an ERP component resulting from the participant’s motor preparation, the contingent negative variation (CNV). In the context of the cued attention protocol, the CNV would be derived by ensemble averaging an appropriate number of EEG records obtained at the central sites (i.e., C3 and C4) that overlie the motor cortices during the S1-S2 intervals of the trials presented. Because greater amplitude of a late CNV component will be observed at the central site contralateral to the hand that is intended for a response relative to that observed at the ipsilateral site (Lutzenberger, Elbert, Rockstroh, & Birbaumer, 1985), motor preparation for the intended hand movement can be measured by CNV asymmetry, which Coles (1989) defined as the lateralized readiness potential (LRP).

The results of a study by Gratton, Coles, Sirevaag, Eriksen, and Donchin (1988) revealed an inverse relationship between RT for hand movement and LRP such that shorter RTs were preceded by larger LRPs. As such, it could be argued that greater stimulus anticipation in the form of enhanced motor readiness of the hand to the side of the anticipated stimulus, as indicated by the magnitude of LRP to directional cueing, would result in attention benefit (but possibly greater cost too, depending on the nature of the concomitant visual attention strategy). It is unclear whether a group difference in motor preparation accounts, at least in part, for any observed differences in attention benefit and cost between persons who are highly experienced in reactive-sport skills and their inexperienced counterparts.

Additionally, several researchers have examined occipital ERPs evoked by the imperative stimuli to assess visual attention during Posner’s cued attention task (Hillyard & Anllo-Vento, 1998; Hillyard, Luck, & Mangun, 1994; Mangun & Hillyard, 1991; McLeod, 1987; Miniussi, Wilding, Coull, & Nobre, 1999). More specifically, the amplitudes of the P1 component, a positive deflection approximately 70–110 ms after stimulus (S2) presentation, and the N1 component, a negative deflection that occurs approximately 125–170 ms after the stimulus, can be quantified (µV) as indexes of selective attention. The P1 reflects both obligatory processing of exogenous stimulus characteristics and the earliest stages of attention whereas the later-occurring N1 primarily reflects endogenous attentional processes. In essence, the results of the studies reveal that the amplitudes of these components are positively related to the direction of attention and can provide insight on the participant’s focus of attention.

The use of ERPs with reactive-sport participants during Posner’s cued attention task seems warranted for detecting the strategies by which such individuals successfully execute very fast responses while dealing with misdirection. The cued attention task provides a controlled setting in which to examine attentional flexibility with a reasonable level of ecological validity, as it contains essential elements of high-speed sport environments. Based on the literature (Castiello & Umilta, 1992; Nougier et al., 1989; 1990; 1991) it is likely that reactive-sport athletes would exhibit a reduction in attention cost, along with a similar or reduced level of attention benefit relative to that of controls, but it is unclear how such an advantage is achieved.
Thus the purpose of the present study was to examine RT behavior, motor readiness, and visual attention processes as assessed by LRP and visual ERPs, respectively, in individuals highly experienced with speeded reactive tasks to determine how they preserve reactivity during a choice RT challenge characterized by uncertainty of stimulus location. As such, the responses of nationally ranked table tennis players were compared to those of controls who were inexperienced with speeded reactive tasks. The involved motor preparation and visual attention processes could be combined strategically in several ways. However, since the majority of trials are correctly cued, it seems reasonable to assume that athletes and controls alike would tend to prepare the hand to the side of the cued location for movement.

This expectation was based on previous research which revealed that both athletes and controls exhibit attention benefit (Castiello & Umilta, 1992); motor preparation for a response to the expected side would likely reduce RT on the validly cued trials relative to neutral ones, and hence contribute to an attention benefit. As greater motor preparation is associated with faster reactions (Gratton et al., 1988), it is likely that both athletes and controls would use motor preparation to reduce RT. Hence it is unlikely that players in either group would fail to engage it. Although it is possible for participants to prepare motorically to respond with the hand contralateral to the cued side (i.e., for the unexpected side), this strategy seems unlikely because it would be disadvantageous in validly cued trials, which constitute the vast majority of trials. Even though this strategy is unlikely, it is possible to detect it with the LRP.1

Based on the constraint that participants would prepare the hand ipsilateral to the cued location, Table 1 lists all possible combinations of motor and visual processes that would comprise comparative preparatory processes. It explains how each comparative strategy results in relative benefit and cost, and identifies those that are consistent with the expected behavioral outcomes.2 Accordingly, the left column of Table 1 identifies five possible motor preparation and visual attention comparative strategies which are compatible with the expected behavioral outcomes, i.e., reactive-sport athletes reduce attention cost while showing similar or reduced level of attention benefit relative to that of controls. The groups’ LRP and visual ERP responses during the cued RT task was contrasted to reveal which of the comparative strategies is characteristic of highly skilled reactive-sport participants.

Methods

Participants

Fifteen male table tennis players (ages 16–35 yrs) who held a U.S. Table Tennis rating of at least 1949 points ($M = 2263.7$, $SD = 230.6$) and 15 male college students (ages 20–32 yrs) with no experience in reactive-sport skills were recruited for this study. All participants were right-hand dominant, were screened for visual and neurological problems, and were each paid $40 for their participation. Prior to testing, participants provided written consent on a form approved by the institution’s human subjects review board.

Warning and Imperative Stimuli

A cued RT task similar to that used by Mangun and Hillyard (1991) was employed. Warning and imperative stimuli were presented on a computer monitor positioned 50 cm in front of the participant. A trial began with the presentation of a
Table 1  Motor Preparation, Visual Attention Strategies, and Expected Behavioral Outcomes for Attention Benefit and Cost for Table Tennis Players (TTP) and Controls (Con)

<table>
<thead>
<tr>
<th>Strategy(^{a})</th>
<th>Motor Prep (LRP)(^{b})</th>
<th>Visual Attn (N1 Ampl)(^{c})</th>
<th>TTP Benefit vs. Con</th>
<th>TTP Cost vs. Con</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ↑ ↑ ↑ ↑</td>
<td>TTP = Con</td>
<td>U E TTP &lt; Con</td>
<td>Reduced (^{1})</td>
<td>Reduced</td>
</tr>
<tr>
<td>– ↑ ↑ ↑ ↑</td>
<td>TTP = Con</td>
<td>E E TTP = Con</td>
<td>Similar (^{2})</td>
<td>Similar</td>
</tr>
<tr>
<td>– ↑ ↑ ↑ ↑</td>
<td>TTP = Con</td>
<td>E+ E TTP &gt; Con</td>
<td>Greater (^{3})</td>
<td>Greater</td>
</tr>
<tr>
<td>2 ↑ ↑ ↑ ↑</td>
<td>TTP = Con</td>
<td>E E+ TTP &lt; Con</td>
<td>Reduced (^{4})</td>
<td>Reduced</td>
</tr>
<tr>
<td>– ↑ ↑ ↑ ↑</td>
<td>TTP &gt; Con</td>
<td>U E TTP &lt; Con</td>
<td>Similar (^{5})</td>
<td>Similar (^{6})</td>
</tr>
<tr>
<td>– ↑ ↑ ↑ ↑</td>
<td>TTP &gt; Con</td>
<td>E E TTP = Con</td>
<td>Greater (^{7})</td>
<td>Greater</td>
</tr>
<tr>
<td>– ↑ ↑ ↑ ↑</td>
<td>TTP &gt; Con</td>
<td>E E+ TTP &gt; Con</td>
<td>Similar (^{9})</td>
<td>Similar</td>
</tr>
<tr>
<td>3 ↑ ↑ ↑ ↑</td>
<td>TTP &lt; Con</td>
<td>U E TTP &lt; Con</td>
<td>Reduced (^{10})</td>
<td>Reduced</td>
</tr>
<tr>
<td>4 ↑ ↑ ↑ ↑</td>
<td>TTP &lt; Con</td>
<td>E E TTP = Con</td>
<td>Reduced (^{11})</td>
<td>Reduced</td>
</tr>
<tr>
<td>– ↑ ↑ ↑ ↑</td>
<td>TTP &lt; Con</td>
<td>E+ E TTP &gt; Con</td>
<td>Similar (^{12})</td>
<td>Similar</td>
</tr>
<tr>
<td>5 ↑ ↑ ↑ ↑</td>
<td>TTP &lt; Con</td>
<td>E E+ TTP &lt; Con</td>
<td>Reduced (^{13})</td>
<td>Reduced</td>
</tr>
</tbody>
</table>

\(^{a}\) Possible combinations of motor preparation and visual attention were reviewed to identify strategies that might yield RT results similar to previous studies which showed that, vs. controls, athletes had reduced attention cost and similar or reduced attention benefit (Castiello & Umilla, 1992; Nougier et al., 1989; 1990; 1991). The range of hypothetical strategies was constrained in two ways. First, the only strategies considered were those in which TTP and Con prepared motorically to respond with hand ipsilateral to expected (cued) side (see note below). Second, as Con were inexperienced with reactive tasks and likely had little opportunity to develop a sophisticated strategy for coping with miscues, they were expected to employ a simple visual-attention strategy by utilizing the warning cues and always visually attending to the expected side. TTP visual-attention strategies were not so constrained because their training history with reactive sports, miscues, and location uncertainty of imperative stimuli may have fostered a more sophisticated strategy vs. Con. From the 13 possible strategies outlined in Table 1, the review revealed 5 consistent with group differences in attention benefit and cost that were reported in the previous research.

\(^{b}\) TTP and Con were expected to prepare motorically to respond with hand ipsilateral to expected (cued) side (↑). Relatively greater motor preparation in one group vs. the other is shown by ↑+. \(^{1}\) U = unexpected: Visual attentional is focused on the unexpected side contralateral to that indicated by the cue. \(E = \) expected: Visual attention is focused on the expected (cued) side. \(E+ = \) Greater visual attention to the expected side relative to the other group.

\(^{c}\) Contrast indicates relative group difference in the strength of visual attention directed to the expected (cued) side.

\(^{1}\) By the first strategy compatible with expected outcomes, both groups would exhibit similar motor preparation for expected location (similar LRP), but TTP would allocate more visual attention to unexpected location (greater P1 and N1 amplitudes to invalidly cued stimuli). This is compatible with a reduction in attention cost in TTP vs. Con, along with a reduction in attention benefit. TTP were expected to have reduced attention benefit because visual attention is directed to the unexpected side, which results in slower RT when the imperative stimulus appears on the expected side as it does in validly cued trials. However, in invalidly cued trials, directing visual attention to the unexpected side will enhance RT and hence also result in reduced cost.

\(^{2}\) TTP and Con would be expected to exhibit similar behavioral outcomes because they do not differ on motor preparation or deployment of visual attention.

(Continued)
TTP would be expected to have greater attention benefit due to greater deployment of visual attention to expected side along with equal motor preparation, enabling them to respond more rapidly when the imperative stimuli are presented on expected side, as in validly cued trials. But they also suffer greater cost when imperative stimuli appear on unexpected side as in invalidly cued trials.

By the 2nd strategy compatible with expected outcomes, both groups would show similar motor preparation for the cued location and attend visually to it, but Con would exhibit greater visual attention to the cued side. TTP would be expected to have reduced attention benefit vs. Con because they direct less visual attention to the expected side in valid trials. However, in the invalidly cued trials they would have an advantage vs. Con and would suffer less cost.

Greater motor preparation gives TTP a relative advantage in validly cued trials, but this would be negated by visual attention directed to the unexpected side. Further, for Con the relative disadvantage in validly cued trials due to lower motor preparation is negated by visual attention directed to the expected side. Hence the expected outcome is similar benefit for both groups.

In invalidly cued trials, TTP would have an advantage due to deploying visual attention to the unexpected side. But this advantage would be negated by the effects of motor preparation. For Con the relative advantage due to lower motor preparation is negated by the effects of visual attention directed to expected side. Hence the expected outcome is similar cost for both groups.

TTP would be expected to have greater benefit due to relatively greater motor preparation for the hand ipsilateral to expected side, which would enhance RT in validly cued trials. In invalidly cued trials, greater motor preparation would be a disadvantage for TTP and result in greater cost for them.

Relative to Con, TTP’s greater motor preparation for the hand ipsilateral to expected side and their greater visual attention to expected side would result in greater attention benefit. But their motor preparation and visual attention would also result in greater cost in invalidly cued trials.

TTP’s relative advantage due to greater motor preparation would be offset by Con’s advantage due to relatively greater visual attention to the expected side, resulting in a similar benefit in validly cued trials. Conversely, TTP’s relative disadvantage in invalidly cued trials due to motor preparation would be offset by Con’s relative disadvantage due to their greater visual attention to the expected side, thus yielding similar outcomes on attention cost.

By the 3rd strategy compatible with expected behavioral outcomes, TTP would be expected to suffer reduced benefit due to their relatively lower motor preparation and the effects of directing visual attention to unexpected side. They would also enjoy reduced cost in invalidly cued trials due to relatively less effort needed to overcome the effects of motor preparation for expected side.

By the 4th strategy compatible with expected behavioral outcomes, reduction in benefit is due solely to TTP’s lower motor preparation. Conversely, the lower motor preparation for responses to the expected side means that when the imperative stimulus appears on unexpected side, TTP reserve more motor preparation for it and can respond more rapidly than Con. Both direct their visual attention in a similar manner, hence visual attention does not contribute to benefit or cost.

In validly cued trials, TTP’s relative disadvantage due to lower motor preparation is offset by greater visual attention to expected side. Con’s advantage due to greater motor preparation is offset by lower visual attention to expected side. Hence neither group gains an advantage in validly cued trials. In invalidly cued trials, TTP’s lower motor preparation for expected side is an advantage, but it is offset by greater visual attention directed to wrong (i.e., expected) side. Con’s disadvantage due to greater motor preparation to expected side is offset by an advantage from lower visual attention to expected side. Thus neither group suffers greater cost in validly cued trials.

By the 5th strategy compatible with expected behavioral outcomes, reduction in benefit would be expected for TTP due to combined effects of lower motor preparation and visual attention to expected side. But cost would also be reduced because lower motor preparation and visual attention to expected side reserve more preparation and attention for invalidly cued trials.
warning cue which was displayed in the center of the monitor for 200 ms. The cue provided information on spatial location of the upcoming imperative stimulus (i.e., to the left or right side of the screen) or was neutral as to directional probability. The directional warning cue consisted of either a left- or right-pointing arrow. Left and right arrows were presented in random order across trials and were equally likely to occur; arrows correctly indicated the location of the imperative stimulus 76% of the time. The directional cue was a white stimulus in the center of the screen on a black background and subtended $3.3^\circ \times 2.5^\circ$ of visual angle. The neutral warning cue was a cross. The imperative stimulus was a vertical bar that subtended $3.3^\circ (h) \times 0.8^\circ (w)$ of visual angle and was presented for 200 ms on the monitor at a position $12^\circ$ of visual angle to either the left or right of a central fixation point.

The participant responded via a computer mouse, depressing the left button with the index finger of the left hand in response to stimuli presented on the left side of the screen. The right button was depressed with the index finger of the right hand in response to stimuli on the right side of the screen. A fixed interstimulus (S1-S2) interval of 1,500 ms was employed. Imperative stimuli were presented to the left and right locations with equal probability. The intertrial intervals were 3,000 ms.

**EEG Recording**

EEG was recorded from surface tin electrodes attached to the scalp at left and right central (C3, C4) and occipital (OL, OR) sites, each of which was referenced on-line to the left ear (A1). Recordings were subsequently re-referenced off-line to averaged ears by recording a separate channel for A2-A1 and transforming the EEG time series off-line using a linear derivation that adjusted the sites of interest (C3, C4, OL, and OR) according to the observed voltage record at A2. Sites C3 and C4 were selected because they lie over the motor cortex (Homan, Herman, & Purdy, 1987). OL was located halfway between T5 and O1, and OR was located halfway between T6 and O2 in the extrastriate region. These occipital locations were included in the study rather than O1 and O2 because of their greater sensitivity to attention processes (Mangun & Hillyard, 1991).

Vertical and horizontal electro-oculograms (VEOG and HEOG, respectively) were continuously recorded using bipolar configurations of 10-mm Grass gold-plated cup electrodes (model E5GH) located above and below the right eye for VEOG and at the temporal canthi for HEOG. Ground was maintained at FPz. Impedance at each electrode site was maintained at or below 5 Kohm. The difference between homologous pairs of scalp electrodes was maintained within 500 ohms. EEG was amplified 50,000 times using Grass model 12A5 Neurodata Acquisition amplifiers with bandpass filter settings of 0.01–100 Hz while EOG was amplified 5,000 times. A 60-Hz notch filter was also used during data collection. Amplifiers were calibrated prior to each testing session with a 10-Hz, 50-µV sinusoidal input signal that was presented to all channels simultaneously. Data were acquired at a sampling rate of 256 Hz using Neuroscan software (version 4.0) on a Gateway 2000 Pentium computer.

**Procedure**

After arriving at the lab, each participant was informed about the requirements of the experiment and was invited to ask questions before signing the approved consent form. Electrodes were then attached and impedance was checked. The participant was then led into a sound-attenuated chamber for testing and was given
a description of the task. He was informed that the warning cue would correctly indicate the location of the imperative stimulus 76% of the time for the directionally cued trials and that, when the neutral warning cue was presented, the left and right imperative stimulus locations would be equally probable. The participant was instructed to fixate his gaze on a central point on the computer screen throughout the test, respond as rapidly and accurately as possible, and respond with the index finger corresponding to the side of the screen on which the imperative stimulus was presented. A practice session of 31 trials was then presented.

Following practice, the participants completed twelve 5-min blocks of trials, 62 trials per block. The protocol yielded a total of 744 trials, of which 456 were directionally cued correctly, 144 were directionally miscued, and 144 were neutral. EEG, VEOG, and HEOG were recorded continuously throughout each block of trials. RT was recorded to the nearest ms. Motivation to perform the task was assessed prior to each block via a visual analog scale similar to that employed to assess mood (Bond & Lader, 1974; Folstein & Luria, 1973). The scale consisted of a 100-mm line anchored by the words “not motivated” and “highly motivated.” Participants responded by drawing a vertical line through the scale at a location corresponding to their level of motivation.

Responses were scored by measuring the distance in mm from the end of the scale anchored by “not motivated” to the mark made by the participant, with a higher score indicating higher motivation. Participants rested for 2 min between each block of trials. There was some concern that the protocol in the current study would be confounded by differences in arousal between the cued and neutral stimulus conditions (Jonides & Mack, 1984). However, analysis of CNV amplitude averaged across C3 and C4, which is associated with arousal (Timsit-Berthier, 1993), showed no such difference between conditions. Hence there was no difference in arousal levels. This finding is in agreement with that of Nougier et al. (1989).

Data Processing

The analyses were restricted to trials on which the participants responded with the correct hand and for which RT was within 1 SD of the participant’s mean. This was done to eliminate trials that were not representative of the participant’s typical response pattern. The EEG records of acceptable trials were first examined for artifact. Epochs contaminated with EOG artifact were “corrected” or transformed in order to remove the influence of blinks and lateral eye movements (Semlitsch, Anderer, Schuster, & Presslich, 1986). Additionally, epochs containing amplitude excursions greater than ±100 µV were excluded from further analysis.

The analysis of CNV data was restricted to the directionally cued trials (i.e., whether the cue was valid or invalid) in order to determine the degree of motor preparation for the stimuli in the expected locations. LRP was derived using Cole’s (1989) formula: LRP = (Mean amplitude difference for intended left-hand movement [i.e., C4 – C3] + Mean amplitude difference for intended right-hand movement [i.e., C3 – C4]) / 2. The values for C3 and C4 in the formula were the mean CNV amplitudes over the final 200 ms of the S1-S2 interval that ended with the presentation of the imperative stimulus. The baseline used to derive the CNV was defined as the mean voltage of a 100-ms interval prior to the warning cue stimulus, S1. The procedure for LRP derivation controlled the influence of factors contributing to laterality that were not related to motor preparation.
ERPs were derived from EEG records obtained from the occipital sites, OL and OR, which were contralateral to the imperative stimulus since stimuli presented to a given hemifield in the participant’s visual display are primarily processed by the visual cortex on the opposite side. In order to render a similar signal-to-noise ratio for the derivation of ERP for the cued conditions, the condition/hand combination yielding the fewest correct trials determined the number of trials that were randomly selected from the other combinations of condition and hand. For example, a participant may have yielded 220 correct left-hand and 180 correct right-hand responses to validly cued stimuli, and 55 correct left-hand and 65 correct right-hand responses to miscued stimuli. In this case 55 trials would be randomly sampled in the other cued condition/hand combinations. Accordingly, ERP records were based on a mean of 53.4 (SD = 12.3) trials per hand with a possible maximum of 72, given the constraint imposed by the miscued or invalidly cued condition.

P1 and N1 amplitudes were defined as the mean amplitudes computed over latency windows centered approximately on the components’ peak latencies in ensemble-averaged waveforms generated by a participant for the validly cued, neutral, and invalidly cued stimuli, respectively (70–110 ms and 125–170 ms after the presentation of S2 for P1 and N1, respectively). The baseline for determining P1 and N1 was defined as the mean voltage of a 100-ms interval prior to the imperative stimulus.

Results

Separate two-tailed t-tests for independent means revealed that there were no differences on ratings of motivation to perform the task between the table tennis players (M = 74.9, SD = 15.3) and controls (M = 77.2, SD = 10.1), t(28) = –0.48, p > .05, or on the number of incorrect responses during the cued trials, t(28) = –0.25, p > .05. The mean number of incorrect responses for table tennis players and controls was 7.9 ± 2.3 and 8.9 ± 3.2, respectively.

RT Data

Reaction times for right- and left-hand responses were averaged and subjected to a 2 × 3 (Group × Cue) ANOVA, with repeated measures on the last factor. The analysis revealed significant main effects for group, F(1, 28) = 11.0, p < .003, and cue, F(2, 56) = 188.3, p < .001. Table tennis players (M = 255 ms) exhibited significantly shorter RT than controls (M = 299). Further, post hoc analysis using the Newman-Keuls procedure revealed that the three cue conditions differed significantly. Mean RT was shortest in the validly cued condition (M = 263 ms) and longest in the miscued condition (M = 293 ms). Mean RT in the neutral condition was 276 ms. Notably, the Group × Cue interaction was not significant, indicating there was no difference between groups in attention benefit and cost. Table 2 lists the RTs of the TTP and C groups for the valid, neutral, and invalidly cued trials.

<table>
<thead>
<tr>
<th>Table 2 Mean Reaction Times (± SD) as a Function of Group and Cueing Condition</th>
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<tbody>
<tr>
<td>Group</td>
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<tr>
<td>Table Tennis Players</td>
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<tr>
<td>Controls</td>
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Figure 1a — Grand-average waveforms obtained at central (C3, C4) and occipital (O1, O2) electrode sites from table tennis players (n = 15) and controls (n = 15) during neutral (noncued), validly cued, and invalidly cued trials. A warning stimulus of either a left- or right-pointing arrow or a cross was presented at Time index 0. (Cont.)
Figure 1b — (Cont.) The imperative stimulus, a vertical bar at 12° of visual angle to the left or right of a central fixation point, was presented at Time index 1500. Responses were made with the index finger on the hand ipsilateral to the imperative stimulus. The N1 and P1 components of the event-related potentials are marked on the relevant electrodes, i.e., occipital site contralateral to the response hand.
Figure 1c — (Cont.) The CNV component is evident in both central electrodes for left and right imperative (S2) stimuli but is marked in only one of the relevant panels. The lateralized readiness potential was based on the maen voltage of the 200-ms phase of the CNV immediately preceding the imperative stimulus.
EEG Data

Figure 1 shows the grand-averaged EEG time series of the TTP and C groups for both left and right imperative stimuli recorded at each central and occipital site (C3, C4, OL, and OR) in response to the neutral, valid, and invalidly cued stimuli. The CNV difference waveforms or LRP s obtained for the entire S1-S2 interval for each group are shown in Figure 2. A one-tailed $t$-test for independent means revealed that TTP ($M = -1.42 \, \mu V; SD = 1.00$) exhibited a significantly greater mean LRP to the cued stimuli than the controls ($M = -0.80, SD = 0.59$), $t(28) = -2.05, p < .025$.

Figure 3 shows the grand-averaged EEG activity at the ipsilateral and contralateral central sites in relation to the direction of the warning cue for both the TTP and C during the last 200 ms of the S1-S2 interval that coincides with the period during which the LRP were quantified.

Figure 4 shows the ERPs obtained from OL and OR in response to imperative stimuli for each cueing condition (valid, miscued, and neutral) averaged across contralateral visual hemifields. Although not shown, P1 and N1 amplitudes were greater at the occipital site contralateral to the location of the imperative stimuli as compared to the ipsilateral site, which confirmed the validity of the electrophysiological record of visual processing. P1 and N1 amplitudes obtained from the sites contralateral to the imperative stimuli were subjected separately to $2 \times 3$ (Group $\times$ Cue) analyses of variance (ANOVA) with repeated measures on the cue factor.

The analysis revealed a significant Group $\times$ Cue interaction for N1, $F(4, 110) = 2.9, p = .025$. Post hoc analysis revealed that the mean N1 amplitude for the table tennis players was significantly greater than that of the controls in response to the miscued or invalidly cued imperative stimuli, while no significant differences were observed between groups in response to the validly cued and neutral imperative stimuli. Further inspection of the means revealed that the mean N1 amplitude for the miscued stimuli was significantly greater than that for the validly cued stimuli in the table tennis players, but no such within-group difference was observed in the

![Figure 2 — Grand-average lateralized readiness potentials (LRP) for table tennis players and controls. Vertical line marks the onset of the warning stimulus. Averages are time-locked to the warning stimulus. LRP s were calculated as the grand-average of the mean of $C_4 - C_3$ amplitude difference for left-cued trials and the mean of $C_3 - C_4$ amplitude difference for right-cued trials. The warning-imperative stimulus interval was 1,500 ms in duration.](image-url)
control group. Figure 5 shows the N1 amplitudes for the TTP and C in response to each cued condition. There were no significant effects for P1 amplitudes. Mean P1 amplitudes and associated standard errors for each cue condition are presented as a function of group in Table 3.

**Discussion**

**RT Findings**

The present study subscribed to a multilevel analysis of attentional processes in highly skilled reactive-sport participants to determine the unique way in which they respond so swiftly to stimuli characterized by location uncertainty. This was accomplished by comparing the reactions, motor preparation, and visual attention processes in nationally ranked table tennis players and controls during the Posner cued attention task. Notably, both groups achieved a benefit from valid cueing and also suffered a cost from invalid cueing. However, the magnitude of reduction in RT for the validly cued trials and the increase in RT for the miscued trials relative to the neutral condition were the same for both groups. Hence there was no difference between groups in either attention benefit or cost, leading to the unexpected finding that the table tennis players did not exhibit greater attentional flexibility than the controls; the failure to observe any group differences for attention benefit and cost is inconsistent with the findings of other researchers.

Although most studies have revealed that reactive-sport athletes exhibited less attention cost to miscued stimuli vs. nonathletes, they also showed that athletes typically suffered a reduction in attention benefit to validly cued stimuli as well (Nougier et al., 1989; 1990; 1991). However, in contrast to the findings gener-
ally reported in the literature, the table tennis players in the present study, when compared to the controls, had no such reduction in attention benefit nor did they incur any greater cost in the miscued trials. Moreover, they were able to maintain superior overall reactivity while responding with greater celerity to all types of imperative stimuli whether preceded by valid, invalid, or neutral cueing. The table tennis players did not suffer any increase in volatility of reactive behavior while dealing with uncertainty of spatial location of the imperative stimuli. They were able to execute their responses consistently and effectively without incurring any decrease in attention benefit relative to controls.

In light of the lack of any group differences on the behavioral indices of attention benefit and cost, it would appear from examination of RT that both groups employed the cue information similarly to prepare their speeded responses. Yet the psychophysiological measures revealed that the groups did in fact employ different

Figure 4 — Grand-average waveforms showing N1 component obtained at electrode sites OL and OR from table tennis players and controls during neutral (A), validly cued (B), and invalidly cued (C) trials. The imperative stimulus was presented at Time index 0.
visual attention and motor-preparation strategies. Specifically, as evidenced by their larger LRPCs, the table tennis players exhibited greater motor preparation for the hand to the side of the spatial cue than did the controls. This difference cannot be explained either by motivation or speed/accuracy tradeoff, as the groups reported similar motivation on the VAMS scale and were undifferentiated on the number of incorrect responses, respectively.

The benefit of cueing on RT in both groups is likely explained by response preparation, as both groups exhibited a motor preparatory response (i.e., LRP) to the warning cue. Interestingly, heightened motor preparation, as indexed by a larger LRP, has been associated with shorter RT (Gratton et al., 1988). Accordingly, the athletes in the present study would have been expected to exhibit shorter RTs to the validly cued stimuli (i.e., greater attention benefit) and longer RTs to the miscued stimuli (greater attention cost). Hypothetically, the increased cost for miscued stimuli would be explained by the need to respond in a channel other than the one initially activated. Such a state would by itself result in a slower RT or greater cost. However, as noted, the groups did not differ on cost or benefit.

Table 3  Mean (± SD) P1 Amplitudes (µV) for Cue Conditions as a Function of Group

<table>
<thead>
<tr>
<th>Group</th>
<th>Validly Cued</th>
<th>Neutral</th>
<th>Miscued</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athletes</td>
<td>1.1 (1.9)</td>
<td>1.3 (1.9)</td>
<td>1.1 (2.3)</td>
<td>1.1</td>
</tr>
<tr>
<td>Controls</td>
<td>0.3 (2.0)</td>
<td>0.6 (1.7)</td>
<td>0.6 (2.4)</td>
<td>0.5</td>
</tr>
<tr>
<td>Average</td>
<td>0.7</td>
<td>0.9</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

Note: Amplitudes were averaged across OL and OR.
Preparatory Strategies

The lack of differences in benefit and cost may be explained by a possible visual attention strategy adopted by the table tennis players who, unlike the controls, exhibited larger N1 amplitudes to the miscued vs. the validly cued stimuli, i.e., the inverse cueing effect. This finding is in agreement with Eimer (1993), who attributed such an effect to mismatch negativity that was elicited by the invalidly cued stimuli. In this regard, the appearance of the invalidly cued or unexpected stimuli evokes a “surprise” response that results in increased processing negativity. This would seem possible. However, an alternative explanation is also tenable—that the table tennis players responded to the directional cues by visually attending more to the low probability or unexpected location in order to attenuate attentional cost. In this manner the speed of reaction by the table tennis player to any unexpected stimuli would have been maintained by sensory gating (increased attention to a particular locus amplifies the receptivity of stimulus properties). This explanation is plausible for several reasons.

First, Mangun and Hillyard (1990) found that individuals can voluntarily allocate significant amounts of attention to particular locations in the visual field while fixating on a central focal point. Their results support the proposition that the participants in the present study volitionally attended more to the location where a low-probability stimulus would appear. Furthermore, it is likely that table tennis players would have reserved some attention for the less probable location, as they are trained to prepare for unexpected events and guard against the consequences of misdirection (Nougier et al., 1989).

Second, visual attention and motor response selection are controlled by distinct mechanisms (Pashler, 1991). Therefore it is possible to prepare a motor response for one stimulus location while orienting attention to another. Although such a strategy is not likely with participants inexperienced in reactive tasks, the present study examined exceptional athletes who were remarkable in terms of their training history and facility with competitive high-speed reactive sports. In light of the table tennis players’ greater LRP to prepare the hand for movement to the side of the expected stimulus, and the greater N1 amplitude to the unexpected stimuli, it seems they were better prepared in the motor domain for the more likely spatial site while also directing their visual attention to the less likely spatial site in preparation for the unexpected event. This diversification strategy may have enabled them to maintain or preserve the integrity of their reactivity across the varying conditions, thus achieving consistency in the speed of response even when faced with stimulus uncertainty.

Reduction of volatility and ability to maintain consistent motor behavior is a hallmark of superior sport performance (Hatfield & Hillman, 2001). Accordingly, any expected group differences in the magnitude of the attention benefit and attention cost for RT outcome on the basis of greater motor readiness to the direction of the cue would have been eliminated, due to the strategy adopted by the table tennis players. Although cost was not reduced in the present sample of table tennis players, it is noteworthy that most athletes in previous studies also achieved less benefit than controls. The athletes in the present study were able to maintain this advantage similar to the controls. Finally, if the increased N1 amplitude was due to a “surprise” because attention was devoted to the expected location while the cue appeared in the unexpected location, as would be consistent with the mismatch negativity
explanation, then one would expect greater attention cost in light of the additional time required to shift attention. However, as noted, this was not the case.

**Absence of Valid Cueing Effect**

Although the strategy outlined above would explain the absence of a valid cueing effect in the TTP, the failure to find the effect in the control group seems plausible in terms of the attention demand involved in the present task. Eimer (1993) also failed to find such an effect for both the P1 and N1 components when “the task was not difficult enough for subjects to direct their attention fully to the visual field indicated by the precue” (p. 414). In fact, Eimer observed that the N1 amplitude was more negative in response to validly cued stimuli only when the task presented to the participant was attentionally demanding. As such, the absence of any cueing effect in the control group may have been due to the low level of attention required to process the imperative stimuli. In addition, the protocol used in the present study employed central as opposed to peripheral directional cueing. According to Jonides and Irwin (1981), two types of cues have been used in the study of spatial attention. The central warning cue, as used in the present study, leads to slower, controlled, and voluntary orienting processes. Alternatively, the peripheral cue elicits fast, reflexive, automatic attention shifts.

The current study employed a central warning cue that allows participants to deploy attention voluntarily. Thus the cueing effects were not obligatory and could have been processed in a variable manner. Also, the instructions emphasized both speed and accuracy. As a result, the control group may have ignored the cue so that no trial would be missed or sacrificed. Of course this is speculation, but such a strategy would essentially weaken the distinction for control-group participants between validly and invalidly cued stimuli. Finally, most ERP studies on spatial attention adopt sustained attention protocols, i.e., the participant’s attention is directed to a given area for several consecutive trials such that his or her directional focus is consistently maintained, while the current study employed a trial-by-trial cueing paradigm. Apparently ERP amplitude modulation is generally smaller in the trial-by-trial cueing paradigm than in the sustained-attention paradigm. Hence the smaller attention modulation effect, the possible attention strategies mentioned above, and lack of any discrimination task associated with the imperative stimuli may well explain the nonsignificant N1 cueing effects in the control group.

Of course all these arguments would also apply to the P1 amplitude which also showed no valid cueing effect, especially since the earlier P1 potential is largely due to exogenous stimulus processing and thus is even less engaged by the low-level attention demands beyond stimulus location in the present study. Using a simple RT protocol, as opposed to a choice RT task as in the present study, Mangun and Hillyard (1991) did observe an effect on P1 amplitude. However, Eimer (1993, 1996) used a protocol similar to that in the current study and did not observe such an effect for P1. According to Eimer (1993), the P1 effect is dependent on (a) tasks that require perceptual discrimination that is highly attention-demanding or (b) tasks that require participants to focus on the cued site.

The task in this study was one of simple detection and not discrimination. Thus the participants probably did not focus their attention to the cued location at the processing stage indexed by P1. Additionally, protocol differences between Mangun and Hillyard’s study and the present study might account for different P1 findings. In the former study the participants had to respond to the imperative stimuli
with the right hand only. Their task depended mainly on sensory preparation. In the current study the participants had to respond to the imperative stimuli with either hand depending on the location of the imperative stimuli. As the task depended on both sensory and motor preparation, the latter could have divided their focus and reduced their ability to allocate attention at the very early processing stage.

Summary

Examination of attention processes in skilled sport participants may be aided by the inclusion of EEG-derived measures as well as RT behavioral outcomes (Abernethy, 2001). In this regard the results of the present study raise concern about the sole use of behavioral outcome measures such as RT to derive understanding of this important process. A multilevel analysis would facilitate our understanding (Cacioppo & Berntson, 1992). In the present study the RT-derived measures of attention benefit and cost were insensitive to strategic differences between table tennis players and nonplayers whereas the groups were differentiated on EEG-derived indices of attention (N1 amplitude) as well as motor preparation (LRP).

Collectively, the present findings along with those of other researchers imply unique attention strategies when dealing with misdirection in individuals who are experienced with open or reactive-sport settings. With a multilevel analysis of the problem, a clearer picture emerged to explain how athletes differ from nonathletes in terms of their attention processes during stimulus uncertainty. As stated above, the N1 results could be interpreted to mean that the table tennis players attended to the less probable spatial site (i.e., miscued) more so than the controls. This strategy is in agreement with the notion that reactive-sport athletes are cautious in terms of the influence of cues vs. miscues from opponents and are trained to prepare for unexpected events (Nougier et al., 1989). After reviewing relevant studies, Nougier and Rossi (1999) concluded that elite athletes prefer to pay more attention to less probable events and are less attentive to more likely events so as to minimize the attention cost in demanding and complex situations.

Additionally, the athletes in the present study made strategic use of the warning cue by exhibiting greater motor preparation for the high-probability event. Apparently they visually prepared for unexpected stimuli while also preparing in the motor domain for the higher probability events. This strategy is consistent with the findings reported for cricket players who used preliminary visual cues to prepare for foot movement (McLeod, 1987). In the simple button-press task used in the present study, this strategy evidently did not result in a significant advantage in terms of RT. However, it could yield a significant advantage for performance in real-life sport situations involving more complex motor responses and movements that require sophisticated response preparation.

Although the task in the present study presented stimulus uncertainty, it is highly simplified relative to the complex situations that fast-action-sport athletes encounter. The warning cue did not provide information with 100% certainty, and is similar to the demands confronted by athletes during competition. In general, reactive-sport athletes anticipate the actions of their opponents and prepare accordingly. Anticipation with 100% confidence would be very costly. Studying the attention deployment and motor preparation strategy of athletes through multiple levels of measurement provides rich information on the underlying attention processes operating in challenging real-life situations, and the detection of such processes could facilitate the instructional cues coaches give to athletes in training for such sports.
References


Notes

1. The valence, negative or positive, of the LRP can be used to interpret which hand is being readied for action. Motor preparation for the hand ipsilateral to the cued side would be revealed by a negative LRP value whereas for the hand contralateral to the cued side it would be revealed by a positive LRP value. Lack of LRP indicates lack of commitment to directional cue. In this manner the valence and magnitude of LRP can help determine whether participants are preparing to react to the cued stimulus location, the unexpected location, or not committing to either direction, which would be indicative of equitable motor readiness.

2. Beyond these strategies, superior attentional flexibility could be achieved by both enhanced motor preparation and increased visual attention to the cued stimulus location along with superior ability to shift attention to the less likely location, if in fact that is where the imperative stimulus appeared. Unfortunately, it is not possible to assess the dynamic processes involved in attention shift, since ERPs are recorded in a time-locked manner before or after the presentation of discrete stimuli. In this regard the preparatory (i.e., LRP) and reactive processes (visual ERPs) are limited to those that can be captured *only in anticipation or in response* to discrete events presented during S1 and S2. Yet the information gained through ERP recording still provides substantial insight on the participants’ covert attention strategies.

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