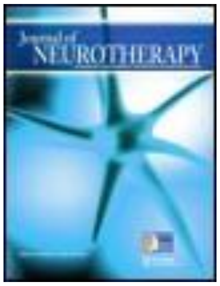

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Direction of SMR and Beta Change with Attention in Adults

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Direction of SMR and Beta Change with Attention in Adults

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ABSTRACT. *Introduction.* The aim of this study was to clarify the interpretation of sensory-motor rhythm (SMR; 13–15 Hz) and beta (16–20 Hz) changes with respect to attention states.

Method. For this purpose, EEG was recorded from 11 participants during (a) a multiple object tracking task (MOT), which required externally directed attention; (b) the retention phase of a visuo-spatial memory task (VSM), which required internally directed attention and avoidance of sensory distraction; and (c) the waiting intervals between trials, which constituted a no-task-imposed control condition. The 2 active tasks were consecutively presented at 2 difficulty levels (i.e., easy and hard). Two analyses of variance were conducted on EEG log spectral amplitudes in the alpha (8–12 Hz), SMR, and beta bands from F3, F4, C3, C4 and P3, P4.

Results. The first 15 analysis compared the MOT to the VSM by difficulty levels and revealed a significant task effect ($p < .0005$) but no effect of difficulty. The results showed that externally directed attention (MOT) resulted in lower values than internally directed attention (VSM) in all three bands. The second analysis averaged the difficulty levels together and added the no-task-imposed reference condition. The results again showed a significant task effect that did not interact with site, hemisphere, or, more important, band. Post hoc tests revealed that both MOT and VSM produced significantly smaller means than the no-task-imposed condition. This pattern of log-amplitude means and the lack of task interaction with any other factor indicate that task-induced attention reduces EEG power in the same proportion across the 3 bands and the 6 channels studied.

Conclusions. These results contradict a frequent interpretation concerning the relationship between the brain's aptitude to increase low beta in neurofeedback programs and improved sustain attention capacities.

KEYWORDS. Alpha, attention, beta, EEG, Neurofeedback, SMR, spectral

INTRODUCTION

Neurofeedback programs for attention deficit hyperactivity disorder (ADHD) involve behavioral training sessions designed to modulate the EEG spectral contents. The aim is typically to reduce excess theta EEG activity (5–7 Hz) and to increase sensory-motor rhythm (SMR; 12–15 Hz) or low beta activity (16–20 Hz; Monastra, Monastra, & George, 2002). These targeted changes are based on quantitative EEG (QEEG)

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observations and are often assumed to directly correspond to increased control over attention and hyperactivity. In sharp contrast to this literature, event-related studies generally present activation as reduced amplitude over both alpha and beta bands (Pfurtscheller & Lopes da Silva, 1999). Because experimental data linking EEG fluctuations to increased attention are scarce, it remains possible that such event-related responses have no parallel in general attention states. The motivation for this study was to better identify the type of modulation of SMR (13–15 Hz) and beta band (16–20 Hz) during sustained attention states, especially compared to a situation in which no task is imposed. This purpose is meant to contribute to our models of how neurofeedback may improve attention. A few studies support the association of increase SMR with increased attention capacity. For instance, Egner and Gruzelier (1994) observed that SMR enhancement training improved performance in both visual and auditory attention tests. Moreover, SMR can be interpreted as a sensory-motor idling rhythm equivalent to occipital alpha that indirectly facilitates visuo-spatial attention. Indeed, Cooper, Croft, Dominey, Burgess, and Gruzelier (2003) observed alpha enhancement when attention benefits from an active inhibition of all visual inputs or of selected parts of the visual field. Correspondingly, learning to increase SMR in ADHD could simply be learning to inhibit the sensory-motor system, that is, mastering how to get calm. Thus, whether increased SMR directly comes from increased activity in an attention network or from sensory-motor disengagement that facilitates attention is still debatable.

In a similar fashion, increased beta (15–20 Hz) amplitude prescribed for ADHD is typically meant to directly support attention and alleviate symptoms of inattentiveness (Egner & Gruzelier, 2004). Indeed, ADHD medication has been reported to increase frontal beta in responders in a manner positively correlated with improvement in a continuous performance test (Loo, Hopfer, Teale, & Reite, 2004). Nevertheless, the relationship of beta enhancement with improved attention remains uncertain since decreasing EEG amplitude over this range of frequencies is sometimes prescribed to increase concentration in high-level executives (U.S. Patent No. 5,740,812, 1998). The rational supporting these opposite prescriptions for increased attention capacity could be simultaneously correct if beta was associated with good attention in opposite directions in children and in adults. This paradox could also be overcome with an alternate view, in which increased beta might represent inhibition or disengagement of a system that hinders attention rather than directly reflect a better attention state. Hence, better attentional capacities could be an indirect effect of reduced background processing reflected in increased beta. Although high beta (above 20 Hz) seems to characterize rumination in depression (Demos, 2005), the low beta band could represent an idling state, akin to the neighboring alpha and SMR bands.

Ray and Cole (1985) approached the relationship between EEG and attention differently. They presented evidence that alpha activity reflects attention demands (external vs. internal attention), whereas beta activity rather reflects emotional and cognitive processing. They contrasted several “external” and “internal” tasks, in which attention must respectively be paid to the external environment or directed to internally held information while resisting distraction from external stimuli (e.g., during mental arithmetic). Internal tasks, which they called “rejection tasks,” were characterized by larger amplitude relative to the external tasks (which they called “intake tasks”), in both parietal lobes, for each 4 Hz-wide band from 8 to 20 Hz. Moreover, all these bands had more energy in the right (R) hemisphere than in the left (L). Finally, their results indicated significant interaction of attention demand (external vs. internal) with hemisphere. These interactions are however questionable, because the analyses were carried on EEG power, rather than on its logarithm, such that even strictly proportional reduction could appear as significant interaction. For instance, the 16–20 Hz band R–L difference was 29 units for internal and 37 units for external, but the corresponding (R–L)/(R + L) ratios were, respectively, 0.130 and

0.135, indicating that the hemisphere differences were nearly proportional to the means. The increased alpha and beta amplitudes observed during the external tasks relative to the internal task are consistent with the active inhibition hypothesis. From a strictly logical point of view, it remains possible that increased alpha reflects sensory input inhibition, whereas increased beta (sought in neurofeedback programs) would reflects increased processing involvement on internally held information.

Although this paradigm revealed locus of attention to be an important alpha and beta band modulator, the Ray and Cole study lacked a neutral control group to help interpreting the difference between the attention demanding internal and external situations. The object of our study is to clarify the relationship of SMR and low beta with attention in normal adults by revisiting the external–internal paradigm with the addition of a neutral no-task-imposed condition. This constitutes a preliminary step to clarify the function of increasing beta through neurofeedback in children with ADHD.

The main hypothesis of this study is based on the event-related studies and proposes that alpha, SMR, and low beta are reduced in amplitude when one of its supporting systems is engaged. Because the attention tasks used do not specifically require sensory motor inhibition, we expected that any spectral difference with the control no-task-imposed condition would consist in amplitude reduction. In line with Ray and Cole (1985), we hypothesized that the internal task would show larger amplitude than the external task in any affected band. In addition to our main hypothesis (reduced EEG amplitude for the external task relative to the internal task), we also expected both experimental tasks to show reduced EEG amplitude compared to the control no-task-imposed condition.

METHOD

Participants

Our study was approved by the ethics committee of the Department of Psychology of Université du Québec à Montréal. Twelve undergraduate students (22–30 years old) were recruited, signed informed consent, and received $25 after their participation in the EEG recording session. Data from one participant had to be excluded because of technical problems.

Experimental Design and Procedure

Two tasks were designed to share the same visual and response interface and were presented at two levels of difficulty (easy and hard). The first experimental condition consisted in a multiple object tracking task (MOT), in which the participants visually tracked designated targets among moving stimuli. The second experimental condition was a visuospatial memory task (VSM), in which the participants had to keep in mind the spatial positions of the stimuli designated as targets. The conditions differed in that the stimuli moved randomly in one condition and temporarily disappeared in the other. Although both tasks recruit the participants' attention toward the spatial location of targets, the MOT and VSM are respectively "external" and "internal" tasks, or "intake" and "rejection" tasks in the sense of Ray and Cole (1985). Indeed, the MOT commands an intense external focus because the participants have to simultaneously follow selected moving objects on the computer screen, whereas on the other hand the VSM task, during the period of stimulus disappearance, requires avoidance of distraction and focuses on the internal representation of the positions to remember.

The MOT trial's procedure consisted of several steps. First, the participant's EEG was recorded during a 6-s period preceding the onset of each trial while the display screen was blank. These EEG data were used as a control condition in which no specific task demand was imposed on the participants. Six to 12 identical blue small squares ($1\,cm^2$) then appeared on the white screen of the monitor. Half of them blinked for 2 s, which defined them as the targets. All objects then moved haphazardly for 10 to 30 s (during which the EEG was collected for this condition). After the stimuli stopped moving, participants were required to identify the targets with the mouse. If the participants lost track of some of the targets, they were asked to click outside the experimental frame rather than guess. Finally, feedback on the trial was provided as the proportion of correctly identified targets along with the display of the correct positions.

To assess whether the tasks' difficulty was an important predictor of EEG fluctuations, the MOT was presented at two levels of difficulty (i.e., easy and hard). These difficulty levels were produced by manipulating: the number of objects, the speed of movement, the predictability of direction change of individual dots, the task duration, and the size of the frame inside which the objects moved.

The VSM trial's procedure consisted of similar steps. The EEG was recorded during a 6-s period preceding the onset of the task while the screen was blank. Between 6 and 16 small squares, identical to those in the MOT condition, then appeared on the screen at random positions. A cross was inscribed inside half of the squares to define them as the targets. The participants were given unlimited time to observe and memorize the targets' locations. At their signal (mouse click), all the squares disappeared for a period of 10, 15, or 30 s (during which the EEG was collected for this condition). After all the squares reappeared at their initial positions, the participants were required to click with the mouse on those previously defined as targets. As in the MOT task, participants were asked to click outside the stimulus zone rather than simply guess. Finally, feedback on performance was given as the trial success rate along with the illustration of the correct positions.

The VSM task was also presented at two difficulty levels, produced by manipulating: the number of objects, the size of the frame inside which object were presented, and the duration of the retention period.

All participants were exposed to both tasks at both difficulty levels. The experimentation contained 48 trials, presented in alternating blocks of 12 of the same type and difficulty level. The starting task was counterbalanced across participants, but the two easy levels always preceded the two harder ones. Electrophysiological recording and data preparation.

The EEG was recorded through a 128-channel BioSemi ActiveTwo system with linked ears reference. The electrodes of interest were those corresponding to the international 10/20 system positions frequently used in neurofeedback: F3, F4, C3, C4, along with the P3 and P4 sites used by Ray and Cole (1985). The EEG signal was filtered with a 0.1 to 45 Hz band pass and then digitized at 256 Hz. The EEG analyses were conducted only on data acquired during the 6-s blank screen stage separating the trials (no-task-imposed) or during the movement or retention intervals of the two tasks.

Trials with behavioral errors were excluded from analysis, as the error could reflect lack of attention, but the waiting period that preceded them was retained for the no-task-impose condition. All EEG epochs retained for analysis (MOT, VSM, and control no-task-imposed) were broken into nonoverlapping 1-s segments, which were inspected visually, blind to condition, and rejected if they contained an artifact. Each retained EEG segment was windowed (raised half cosine on 0.1 s at both ends) and Fourier transformed. The individual spectra within each condition were averaged in the amplitude domain within subject. The resulting average amplitude spectra were then transformed to their base-10 logarithmic values for statistical analyses. The choice of these different units for averaging was based on ranking the mean spectrum among the individual spectra contributing to the mean. This was successively done for amplitude, power, and log power. The form of data for which the mean ranked closest to 50% (the median) across the frequency bands from 1 to 25 Hz was retained. This resulted in applying a logarithmic transform to the averaged amplitude within each participant and condition. The log amplitudes of the various 1-Hz-wide bands within the alpha (8–12 Hz), SMR (13–15 Hz), and low beta (16–20 Hz) bands were averaged together as a final step before statistical analysis of log spectral amplitudes.

Statistical Analyses

Statistical testing was done with a repeated measure analysis of variance (ANOVA), using SPSS MANOVA and by applying the Geisser & Greenhouse correction for effects with more than two levels; in those cases, the degrees of freedom reported are the reduced ones. A first ANOVA, ignoring the waiting condition, implemented the completely within-subject design: 2 Tasks × 2 Difficulty Levels × 3 Bands (i.e., alpha, SMR, low beta) × 2 Hemispheres × 3 Sites (i.e., frontal, central, parietal). Such five-factor analysis yields 31 statistical tests. The effects of Band, Hemisphere, or Site without interaction with Task or Difficulty are not relevant to the purpose of our study. Their presence, however, increases the risk of a type I error because any interaction of Task or Difficulty with Band, Hemisphere, or Site would justify concluding in a Task or Difficulty effect. Consequently, a Bonferroni correction was applied, which set the per-test significance level to $.05/8 = .00625$. Significant effects not involving Task or Difficulty are reported but were not further explored into simple effects or pairwise differences.

Because the first analysis showed no effect of difficulty, the easy and hard conditions could be averaged together within task for the purpose of a second ANOVA, which included the no-task-imposed control as a third level for the Task factor. This analysis (without the Difficulty level) tested 15 different effects, from which only the 8 involving the Task factor were directly relevant to this study. For the same reason as for the first ANOVA, the per-test significant level was set at $.05/4 = .0125$. The comparison of the no-task-imposed condition with each of the other two tasks was a priori justified and the critical level for these contrasts was set at the usual .05 per test.

RESULTS

Behavioral Results

The success rates for the easy conditions were 96.3% of MOT trials and 98.2% of VSM trials. The success rates for the harder conditions were 68.5% of MOT trials and 71.3% of VSM trials. EEG results Figure 1 illustrates the means for the five experimental conditions over the six channels of interest. Given the lack of interaction involving band (see next) and the greater interest for the SMR and beta band (because neurofeedback in ADHD targets these more than alpha), the alpha band was omitted to simplify the figure.

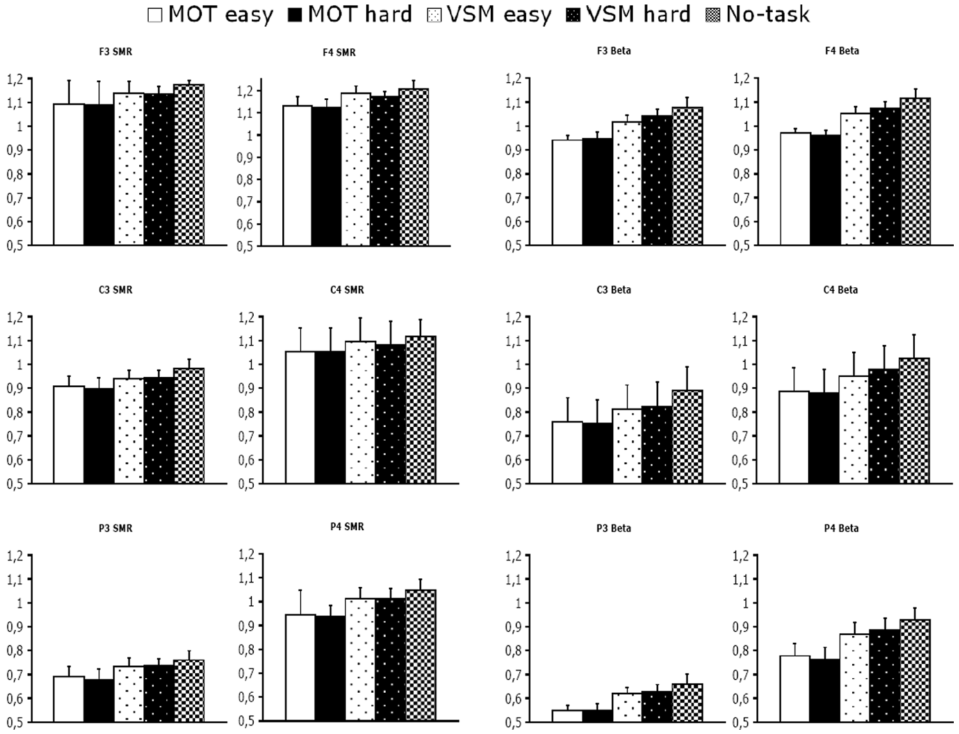
The first ANOVA (Task × Difficulty × Band × Hemisphere × Site) showed 5 significant effects out of the 31 tested. Among the effects of interest, that is, those involving Task or Difficulty, only the main Task effect was significant, $F(1,\ 10) = 33.84$, $p < .0005$. The main Difficulty effect was clearly absent, $F(1,\ 10) = 0.39$, $p = .547$, as well as any interaction effects involving Difficulty.

Of the effects involving neither Task nor Difficulty, all three main effects were significant: Band, $F(1.6,\ 16) = 33.34$, $p < .0005$; Hemisphere, $F(1,\ 10) = 177.68$, $p < .0005$; Site, $F(1.59,\ 15.9) = 492.82$, $p < .0005$; as was the Hemisphere × Site interaction, $F(1.79,\ 17.9) = 74.14$, $p < .0005$.

For the Task effects, the means were 0.959 (±0.027 *SEM*) for MOT and 1.027 (±0.024) for VSM. For the Band effect, the means were 1.136 (±0.036) for alpha, 0.991 (±0.036) for SMR, and 0.853 (±0.022) for beta. The Hemisphere and Site means are reported through their interaction; for frontal, central, and parietal, respectively, the means were 1.123 (±0.023), 0.925 (±0.028), and 0.713 (±0.025) for the left hemisphere and 1.162 (±0.025), 1.070 (±0.032), and 0.968 (±0.029) for the right hemisphere. This interaction thus indicates that hemisphere difference grows from front to back (0.038, 0.145, and 0.255 respectively). Because the measures were in log units, these R–L differences are also the logarithm of the R/L amplitude ratio.

The real interest of our study lies in the comparison with the condition in which no task was imposed on the participants. Because the initial ANOVA indicated that the two difficulty levels were too similar to be reflected differently in the EEG

FIGURE 1. Mean log-10 amplitude in the multiple object tracking task (MOT; easy and hard), the visuospatial memory task (VSM; easy and hard), and the no-task-imposed conditions in the sensory-motor rhythm (SMR) and the beta bands over f3, f4, c3, c4 and p3, p4. note. Error bars represent standard errors of the means.



spectra, the data could be averaged across difficulty levels for a second analysis involving the control no-task-imposed condition. There is little surprise that all significant effects of the first ANOVA are still present after adding a third Task level: Task, $F(1.37, 13.7) = 20.12$, $p < .0005$; Band, $F(1.55, 15.5) = 30.00$, $p < .0005$; Hemisphere, $F(1, 10) = 179.41$, $p < .0005$; Site, $F(1.59, 15.9) = 522.98$, $p < .0005$; with the only significant interaction being that of Hemisphere by Site: $F(1.72, 17.2) = 97.63$, $p < .0005$. More important, as shown in Figure 1, the results of this second analysis revealed that the mean for the control no-task-imposed condition (1.067 ($\pm$0.036)) significantly differed from each of the active tasks, $F(1, 10) = 24.18$, $p = .001$ for the MOT and $F(1, 10) = 5.82$, $p = .036$ for VSM.

DISCUSSION

The main conclusion from this study is that the involvement in a task requiring attention in young adults causes a reduction in EEG spectral amplitude compared to a condition in which they simply wait for the upcoming trial. As indicated by the lack of interactions, this effect is essentially the same for all three bands across all six recording channels analyzed. Thus, in line with the general principle that brain activation tends to desynchronize neuronal activity, the results of our study reveal that the signature of increased attention is a reduction of alpha, SMR, and beta amplitudes. Therefore, the beta band effect turns out to be opposite to what is often interpreted as the reason why renormalizing low beta (increasing it) through neurofeedback is beneficial for

ADHD. This, however, does not mean that such target should be abandoned. Our data rather challenge the rationale underlying the success of the treatment.

Adding the neutral control condition brings an interesting complement to interpret the results of Ray and Cole (1985). First, our results replicate their hemisphere effect, with larger amplitudes observed for the right than for the left hemisphere for all bands from 8 to 20 Hz. Second, because a multiplicative (i.e., proportionality) model is more appropriate than an additive model to explore EEG amplitudes variations over space, the present results confirm our speculation that the Ray and Cole Task × Hemisphere effects might be illusory. Indeed, their results were not replicated in our analyses that embedded a multiplicative model implemented through logarithmic transformations. Third, while the original data suggested that internal tasks produce increased amplitudes relative to external tasks, we found that the comparison with the no-task-imposed condition rather indicates that it is more appropriate to see this as lesser desynchronization. The lack of interaction of the Task factor with band or with topography leads us to consider that the MOT external task just requires more intense concentration and discredits the hypothesis of an extra motor inhibition during the VSM rejection task. Indeed, we did not find any sign of difference between tasks exclusive to the SMR band or to the central recording sites, which would have suggested a motor inhibition component. This interpretation is therefore consistent with a general decrease in EEG amplitude while performing a cognitive effort (i.e., steadily increasing desynchronization from no-task-imposed to VSM to MOT).

Because the influence of the cognitive effort required to perform the tasks is an important modulator of EEG patterns, the lack of effect regarding the Difficulty factor may seem surprising. Although some studies did find a significant effect of difficulty level on EEG patterns (e.g., Sterman & Mann, 1995), Babiloni et al. (2004) illustrated that the prominent factor for EEG desynchronization is the nature of the cognitive effort rather than its difficulty. They observed that even their easiest task (i.e., the retention of a single item) desynchronized the EEG spectra in the theta and alpha bands. The results of our study revealed a similar effect, extended to low beta frequencies, in which performing the task correctly over 95% of the time desynchronized the EEG as much as the harder task (around 70% of correct answers). This does not mean, however, that still more challenging difficulty levels would not further desynchronize the EEG.

Finally, a Difficulty × Band interaction could have been considered significant if no correction had been applied for the number of tests, $F(1.85, 18.5) = 3.74$, $p = .046$. The means would then show that increasing difficulty level enhanced alpha by 0.013 but decreased SMR and low beta by 0.006 and 0.007 log units, respectively. Although the effect likely constitutes a type I error, its trend would be consistent with extra attention effort reducing SMR and beta rather than increasing their amplitude.

Our study is just a preliminary step in resolving the apparent paradox that attention capacity would be enhanced through neurofeedback by increasing beta in children with ADHD and by decreasing it in adults without ADHD. Although our results only characterize the latter population, a reasonable doubt should be raised that the association between increasing 16–20 Hz beta in children with ADHD and improving their attention capacity in daily life may not be as direct as previously suspected. As suggested earlier, one way to sustain increased beta is possibly to learn to tame an intrusive system that interferes with good management of attention capacities. According to that assumption, the lower part of the beta band should be considered as the idling rhythm of an internal system that would be over activated in ADHD. Such a system might be related to the profusion of distracting thoughts that intrude normal activity in the life of the child.

Identifying experimental conditions to test this hypothesis is a challenging task. Meanwhile, ongoing studies have been undertaken to explore whether comparable results could be obtained in children with and without

ADHD. Should the present EEG data pattern replicate with children, a revised interpretation of the beneficial effect of increasing beta through neurofeedback would become unavoidable.

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