Article

Brain Activity During Resting State in Relation to Academic Performance

Evidence of Neural Efficiency

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Abstract. EEG coherence has been widely used to investigate brain activity and learning. However, relatively little is known about the relationship between resting-state EEG coherence and academic performance. The present study investigated this relationship with 140 healthy, normal participants. EEG was recorded during resting periods, with eyes open for 3 min, and the recordings were analyzed for 64 electrode positions in the theta (4–8 Hz), alpha (8–12 Hz), and beta (12–25 Hz) frequency bands. Coherence, defined as the spectral cross-correlation between two signals normalized by their power spectra, was calculated. Short- and long-range intrahemispheric coherence within each hemisphere and interhemispheric coherence across the left and right hemispheres were then computed and compared for each of the theta, alpha, and beta bands. The results showed that academic performance, as measured by grade point average (GPA), was negatively correlated with short-range intrahemispheric alpha and beta coherences in both hemispheres and with interhemispheric alpha and beta coherences in the temporal cortical regions. Therefore, better academic performers demonstrated more decoupling of brain areas when resting with eyes open. This is consistent with a model that relates decreased coherence to neural efficiency.

Keywords: EEG, academic performance, coherence, neural efficiency

According to the neural efficiency hypothesis (Haier, Siegel, Tang, Abel, & Buchsbaum, 1992; Haier et al., 1988), ''intelligence is not a function of how hard the brain works, but rather how efficiently it works.'' Therefore, brighter individuals may not need to work harder, but do know how to work smarter. Extensive studies have already shown a relationship between neural efficiency and intelligence (Jausovec, 2000; Jausovec & Jausovec, 2003; Neubauer & Fink, 2009) in which highly intelligent individuals display lower brain activation and more coupling in specific task-relevant brain areas while they engage in cognitive tasks. One of the frequently used measures is electroencephalogram (EEG) alpha activity. For instance, average individuals display lower alpha power (or greater mental effort) in solving complex problems than gifted individuals do (Jausovec, 1996, 2000). This difference appears not only in the level of brain activation but also in which neural networks are involved. Measurements of the spatial dispersion in brain activity, as analyzed with low-resolution brain electromagnetic tomography (LORETA), show that individuals of higher intelligence display more spatially coordinated brain activity by engaging inferior right hemispheric brain areas to solve different figural matrices with better task performance, whereas individuals of lower intelligence have to engage superior left hemispheric brain areas to solve similar tasks. Given the fact that the right hemisphere is more involved in figural problem solving, individuals with higher intelligence are able to mobilize more specific and efficient brain networks that are directly related to task performance, whereas individuals with lower intelligence activate brain areas that are not closely related and specific to task performance (Jausovec & Jausovec, 2003). Despite some evidence in favor of the neural efficiency hypothesis, Neubauer and Fink (2009) pinpointed in their review paper that neural efficiency might arise when individuals deal with tasks of subjectively low to moderate task difficulty or after sufficient practice, so participants have already developed appropriate and/or efficient strategies to deal with the task. When highly intelligent individuals deal with very complex tasks, they seem

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to invest more cortical resources, resulting in positive correlations between brain usage and cognitive ability, than less intelligent individuals do.

Recently, there has been increasing interest in EEG activity at rest. Accumulating evidence suggests that the tonic level of arousal may differ between individuals, and EEG activity recorded during a resting baseline condition may be a significant indicator of individual differences (Dunn & Reddix, 1991; McKay, Fischler, & Dunn, 2003). Specifically, higher EEG frequency during resting conditions has been found to relate negatively to intelligence, and the correlations for the eyes-open state are more pronounced than for the eyes-closed state (Jausovec & Jausovec, 2000). Dunn and his colleagues consistently found that when individuals with different cognitive styles were compared, the EEG activity at rest was more predictive than that during task performance, in that a lower baseline alpha level led to better text recall (Dunn & Reddix, 1991; McKay et al., 2003). One recent study (Aguirre-Pérez, Otero-Ojeda, Pliego-Rivero, & Ferreira-Martínez, 2007) further compared EEG activity at rest between high school students with high and low academic attainments. The results showed that students with low academic attainment generally had a higher theta power at rest than those with high academic attainment. In these studies, the EEG activity at rest, either during an eyes-open or eyes-closed condition, was analyzed in terms of power levels at certain frequency bands, such as alpha frequency, to compare the variations in levels of brain activation. Beyond measuring power levels, Petsche (1997) proposed that EEG coherence can provide additional information about functional relations between brain regions. Coherence measures reflect how the connectivity between brain regions differs between individuals in terms of intelligence, cognitive performance, or learning ability. Petsche's proposition has been supported by several studies that revealed a negative correlation between coherence measures and IQ (Jausovec & Jausovec, 2000; Thatcher, McAlaster, Lester, Horst, & Cantor, 1983; Thatcher & Walker, 1985). In a comparison with regular children, mentally retarded children demonstrated a global increase of EEG coherences in all bands (Gasser, Jennen-Steinmetz, & Verleger, 1987). A higher coherence pattern at rest was also observed in children with Down's syndrome (Schmid, Tirsch, Rappelsberger, Weinmann, & Pöppl, 1992), learning disabilities (Leisman & Ashkenazi, 1980), and reading-writing difficulties (Marosi et al., 1995). Therefore, individual differences in brain activity may be revealed not only during performance of cognitive tasks but can also be observed during the resting state, as measured by EEG coherence.

EEG coherence is a measure of linear synchronization between signals at two electrode sites as a function of frequency (Thatcher, Krause, & Hrybyk, 1986). This coherence reflects the degree of functional cooperation between neuronal substrates (Weiss & Mueller, 2003). The examination of temporal synchronization of neuronal activities, which involves calculating coherence between two EEG signals, has provided useful information about the underlying cortical coupling and connectivity between distinct brain regions (Barry, Clarke, McCarthy, & Selikowitz, 2009; Clarke et al., 2008; Weiss & Mueller, 2003). This research has suggested that high EEG coherence indicates strong structural or functional connection between cortical regions (Thatcher, North, & Biver, 2008; Thatcher et al., 1986) and is also associated with various cognitive tasks, such as memory (Klimesch, 1999), language (Cheung, Chan, & Sze, 2009, 2010; Weiss & Mueller, 2003), and intelligence (Thatcher, North, & Biver, 2005). The present study aimed to investigate the relationship between resting EEG coherence and academic performance at school, which has been relatively less examined in the literature. Examining these relationships will be helpful in determining whether the academic achievements of students at school are associated with differences in brain activity at rest. The authors hypothesized that academic performance, like intelligence, will have a negative correlation with resting EEG coherence and that better academic performers will have lower EEG coherence at rest.

Method

Participants

A total of 140 university students (age: 20.83 ± 0.99; years of education: 15.05 ± 0.25; grade point average, GPA: 3.21 ± 0.29; 19 males and 121 females) were recruited from the Institute of Textiles and Clothing at The Hong Kong Polytechnic University. The students' academic performance was evaluated by the cumulative GPA printed on their academic transcript (maximum = 4.00). This was an objective assessment of academic achievement measured over time and was calculated by dividing the number of grade points earned by the total number of credits taken. The study was conducted in accordance with the Helsinki Declaration of the World Medical Association Assembly, and the research protocol was approved by the Human Subjects Ethics Sub-committee (HSESC) of The Hong Kong Polytechnic University. All of the students were required to sign informed consent forms prior to the study, and all participated voluntarily.

EEG Recording

The EEG was recorded from 64 Ag/AgCl-sintered electrodes mounted on a stretch-Lycra Quik-Cap (Neuroscan, El Paso, TX, USA), with electrode placement in accordance with the international 10-10 system (Chatrian, Lettich, & Nelson, 1985). A ground electrode was placed on the forehead anterior to Fz. The standard reference electrode of the cap, placed between Cz and CPz, was used during acquisition. Electrode impedances were under 10 kΩ, and homologous sites were within 1 kΩ of each other. Signals were amplified with a SynAmps[2] amplifier unit (Neuroscan) with a bandpass of 0.05–200 Hz and were digitized at a sampling rate of 1,000 Hz. During EEG recording, the subjects were asked to stay fully relaxed while looking at the blank screen of the computer monitor in front of them for 3 min. The eyes-open state was used for EEG recording because EEG activity in terms of power and/or coherence measures during the eyes-open state has been shown to be more prominently related to ability, such as giftedness (Jausovec, 1996), creativity, and intelligence (Jausovec & Jausovec, 2000), and more recently has been considered to better reflect the resting-state networks involved in the default mode of brain function than the eyes-closed state (Chen, Ros, & Gruzelier, 2013).

EEG Data Processing and Analysis

The EEG data underwent offline processing for artifact removal, and were re-referenced to the linked ears using the NeuroGuide version 2.5.2 software (Applied Neuroscience Inc., St. Petersburg, FL, USA) because the averaged earlobe reference [(A1 + A2)/2] is commonly used for EEG coherence analyses (Thatcher et al., 2005). Split-half and test-retest reliability tests were conducted on the selected EEG segments. Only data that had at least 1 min of artifact-free data with > 90% reliability were subsequently entered into the spectral analyses. Fast Fourier Transformation was used to translate signals to the frequency domain. The EEG was analyzed over 64 electrode positions in the theta (4–8 Hz), alpha (8–12 Hz), and beta (12–25 Hz) frequency bands.

Coherence, defined as the spectral cross-correlation between two signals normalized by their power spectra (Thatcher et al., 1986; Thatcher et al., 2005, 2008), was calculated between all the electrode pairs, except for the eight midline electrodes (Fpz, Fz, FCz, Cz, CPz, Pz, POz, Oz). The coherence values were transformed by using Fisher's z-transform, resulting in a Gaussian distribution. In accordance with the published literature (Barry et al., 2009; Clarke et al., 2008; Dupuy, Clarke, Barry, McCarthy, & Selikowitz, 2008), the values obtained were inverse-transformed for reporting. They ranged from 0 to 1, with higher values representing stronger phase synchronization between signals of two electrode pairs. Within each hemisphere, the coherence values between possible electrode pairs were further averaged and categorized into (i) intrahemispheric short-range (between adjacent electrode pairs, such as left: F1-F3, C3-C5, P5-P7 versus right: F2-F4, C4-C6, P6-P8) coherence or (ii) intrahemispheric long-range (with at least one electrode in between, such as left: F1-C1, C3-P3, F5-P5 versus right: F2-C2, C4-P4, F6-P6) coherence. The interhemispheric coherences were separately calculated within

(i) the frontal region (Fp1–Fp2, AF3–AF4, F1–F2, F3–F4, F5–F6, F7–F8),
(ii) the central region (FC1–FC2, FC3–FC4, FC5–FC6, C1–C2, C3–C4, C5–C6, CP1–CP2, CP3–CP4, CP5–CP6),
(iii) the temporal region (FT7–FT8, T3–T4, TP7–TP8),
(iv) the parietal/occipital regions (P1–P2, P3–P4, P5–P6, P7–P8, PO3–PO4, PO5–PO6, PO7–PO8, O1–O2) (Cheung et al., 2009, 2010; Coben, Clarke, Hudspeth, & Barry, 2008; Dupuy et al., 2008).

Results

Intrahemispheric Coherence and GPA

The relationship between intrahemispheric coherence and GPA was determined by using Pearson's correlation coefficients. As revealed in Figure 1, significant negative correlations between short-range intrahemispheric coherence and GPA were obtained in the alpha frequency bands in both hemispheres (left: $r(140) = -0.291$, $p = .000$; right: $r(140) = -0.259$, $p = .002$). It was further shown that intrahemispheric beta coherence was also inversely correlated with GPA, and the association was significant for short-range coherence in both the left ($r(140) = -0.238$, $p = .005$) and right ($r(140) = -0.215$, $p = .011$) hemispheres, respectively (Figure 2). The correlation between long-range intrahemispheric coherence and GPA was not significant ($p > .05$) for the alpha and beta frequency bands. Similarly, no significant correlation was found between short- and long-range intrahemispheric coherence and GPA in either hemisphere for the theta frequency band. Students with higher academic performance, as measured by their GPAs, thus generally had lower short-range intrahemispheric alpha and beta coherences while at rest.

Interhemispheric Coherence and GPA

As revealed in Figure 3, a significant negative correlation between interhemispheric coherence and GPA was found for the alpha ($r(140) = -0.223$, $p = .008$) and beta ($r(140) = -0.258$, $p = .002$) frequency bands. This negative correlation appeared only in the temporal cortical region and not in the frontal, central, or parietal/occipital regions. With regard to the theta frequency band, no significant correlation was found between interhemispheric coherence and GPA in the four cortical regions ($p > .05$). As a result, students with higher academic performance (as measured by their GPAs) had lower interhemispheric alpha and beta coherences between the left and right temporal cortical regions while at rest.

Discussion

The main purpose of this study was to investigate the relationship between resting EEG coherence and academic performance, as measured by GPA, in university students. The results demonstrated that academic performance correlated negatively with short-range intrahemispheric alpha and beta coherences in both hemispheres and with interhemispheric alpha and beta coherences in the temporal cortical regions, as measured during the resting condition. Therefore, consistent with previous findings on intelligence (Jausovec &

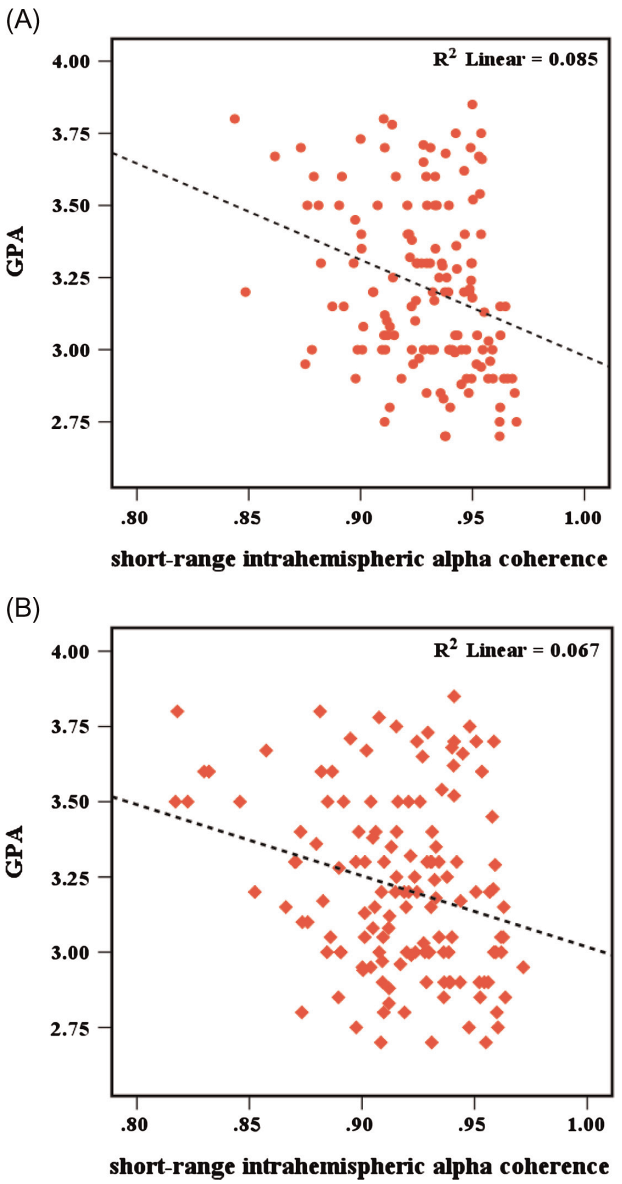

Figure 1. Association between GPA and short-range intrahemispheric alpha coherence in the (A) left and (B) right hemispheres.

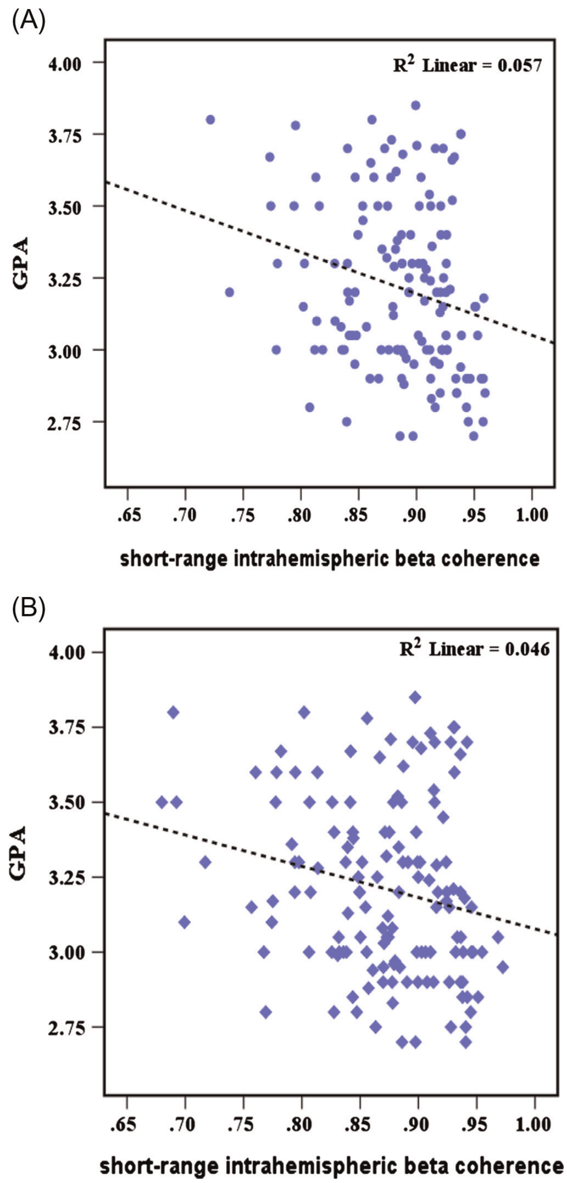

Figure 2. Association between GPA and short-range intrahemispheric beta coherence in the (A) left (B) right hemispheres.

Jausovec, 2000; Thatcher & Walker, 1985; Thatcher et al., 2005), EEG coherence measures at rest are also negatively related to academic achievement. Individual differences can be observed in brain activity during the resting state, and more decoupling of brain areas is found among better academic performers. Given that the EEG was recorded at rest, cognitive demands during the recordings were relatively minimal. Therefore, the observed decoupling of brain areas did in fact provide further empirical support for the neural efficiency hypothesis (Haier et al., 1988, 1992). Haier reported that brighter individuals use their brains more efficiently by allocating an optimal amount of energy resources to cope with each specific task demand. Here, we show that GPA, an assessment of academic achievement measured over time, is related to EEG coherence during the resting state. Certainly, completing a degree depends on various cognitive functions, such as executive function, attention, memory, language, as well as intelligence, and brain activity captured in a 3-min EEG recording may not be able to account for all of these abilities. Although it may be too premature to use EEG recording during the resting state as a screening tool for academic achievement, these findings still provide evidence of the significance of brain activity or connectivity during the resting state, and the difference in academic achievement may not only be related to ability but also to the resting-state networks. In

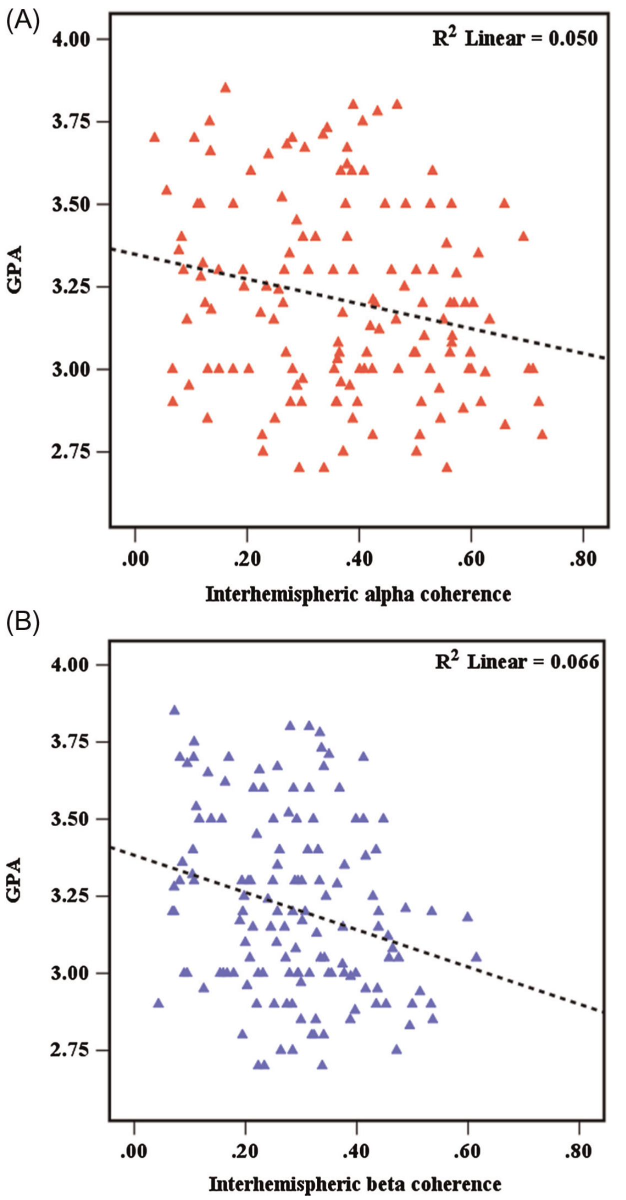

Figure 3. Association between GPA and interhemispheric coherence in the temporal cortical regions for (A) alpha and (B) beta frequency bands.

fact, investigation of resting-state networks, functional connectivity, and the default network of brain function is now being widely carried out by resting-state functional magnetic resonance imaging based on low-frequency fluctuations and/or source-derived EEG analysis with the view that the findings on resting-state networks are significant in explaining individual difference (highly intelligent vs. less intelligent; normal vs. clinical population) in cognitive function and task performance (Broyd et al., 2009; Damoiseaux et al., 2006; Fransson, 2005, 2006; Greicius, Krasnow, Reiss, & Menon, 2003; van den Heuvel & Hulshoff Pol, 2010; Jann et al., 2009; Raichle et al., 2001).

Thatcher et al. (1986) proposed a two-process model of cortico-cortical associations related to coherences that involved short and long neuronal fibers. In this model, decreased coherence in the short neuronal fibers of specialized cell populations is related to increased spatial differentiation and increased complexity of the brain and thus to better processing speed and efficiency of information processing. Our results are compatible with the expectations of the Thatcher et al. model (1983, 1986) in that the higher academic performers generally had lower short-range intrahemispheric alpha and beta coherences in both hemispheres, in contrast to the lower academic performers. Therefore, individual differences in cortical differentiation in mental capacity for information processing are observed in normal adults, particularly in cortico-cortical circuits that involve alpha and beta activities. The observed variation in resting EEG coherence was more obvious for the alpha and beta frequency bands, whereas no significant association was found between the theta frequency band and GPA. One possible explanation is that coherence in higher frequency bands, such as the alpha and beta bands, is more sensitive to cognitive processing. For instance, task-relevant alpha coherence is observed during object recognition (Freunberger, Klimesch, Griesmayr, Sauseng, & Gruber, 2008; Mima, Oluwatimilehin, Hiroak, & Hallet, 2001) and working memory processes (Crespo-Garcia, Pinal, Cantero, Díaz, & Zurrón, 2013; Freunberger, Fellinger, Sauseng, Gruber, & Klimesch, 2009). A variety of findings indicate that an increase in alpha coherence is associated with the synchronization between brain areas that is related to the early semantic encoding of objects (Mima et al., 2001) involved in the processing of the stimulus and/or task (Varela, Lachaux, Rodriguez, & Martinerie, 2001), and during top-down and bottom-up processing (see review Klimesch, Sauseng, & Hanslmayr, 2007; Palva & Palva, 2007, 2011). Coherence in the beta frequency band is associated with attention (Barry et al., 2009; Dupuy et al., 2008) and language processing (Cheung et al., 2010, Weiss & Mueller, 2003). It is thus possible that brighter individuals use these energy resources only when they engage in cognitive task performance. During the resting state, they save the resources by lowering their EEG coherence in these frequency bands. In contrast, individuals with lower academic achievement tend to engage more neural networks during the resting state. Indeed, these results are in line with those of previous studies in that a higher coherence pattern at rest has been observed in children with mental disabilities (Gasser et al., 1987), Down's syndrome (Schmid et al., 1992), learning disabilities (Leisman & Ashkenazi, 1980), and reading-writing difficulties (Marosi et al., 1995). The results of this study suggest that the pattern extends to normal university students.

This was an initial study to investigate the relationship between resting EEG coherence and academic performance. Several limitations should be noted. First, academic performance was measured by the GPAs of university students. Given that the standards for calculation and evaluation of GPAs may vary from one university to another, generalization of the results requires further investigation across different universities. In addition, EEG coherence varies with age. As normal children grow older, they typically show higher coherence values between the vertex and the posterior cortical regions and a decrease in interhemispheric coherence values in the frontal regions (Marosi et al., 1992). Therefore, the pattern observed in the present study may not apply for children and adolescents, and this possibility deserves further study. Previous studies have also found the gender effect to be a moderator variable in neural efficiency (Jausovec & Jausovec, 2008; Neubauer & Fink, 2009). The relationship between resting-state EEG and academic performance might be dependent on or biased by gender. However, due to the biased sample, the gender effect was not taken into consideration in the present study. The preliminary results based on the relatively small sample size of males ($n = 19$) still indicated a negative trend between resting-state EEG and academic performance (r ranged from -0.227 to -0.319), although the trend did not reach significance level (p ranged from .160 to .350). More males should thus be recruited to explore whether sex is a moderating variable in the relationship. In the present study, the association between EEG coherence during the resting state and academic achievement was not observed in the theta frequency band. A recent study suggested that increased large-scale EEG slows cortical oscillatory activity and the associated widespread increase in EEG theta activity during waking may be reliably associated with cognitive processing, such as memory encoding (Kirov, Weiss, Siebner, Born, & Marshall, 2009). It is thus conceivable that the amplitude of the slow oscillations, such as theta activity, may be related to academic achievement, given its involvement in various aspects of memory processing and attention (Babiloni et al., 2008; Sauseng, Hoppe, Klimesch, Gerloff, & Hummel, 2007). Finally, although the study showed that EEG coherence provides medium effect size estimates (Cohen, 1988) of academic achievement over time, other important factors, such as socioeconomic status, familial factors, sleep-wake cycle, employment, and psychological well-being, may also affect academic achievement in school and should be taken into account in future studies.

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References

Aguirre-Pérez, D. M., Otero-Ojeda, G. A., Pliego-Rivero, F. B., & Ferreira-Martínez, A. A. (2007). Relationship of working memory and EEG to academic performance: A study among high school students. *International Journal of Neuroscience, 117*, 869–882.

Babiloni, C., Vecchio, F., Mirabella, G., Buttiglione, M., Sebastiano, F., Picardi, A., ... Eusebi, F. (2008). Hippocampal, amygdala, and neocortical synchronization of theta rhythms is related to an immediate recall during rey auditory verbal learning test. *Human Brain Mapping, 30*, 2077–2089.

Barry, R. J., Clarke, A. R., McCarthy, R., & Selikowitz, M. (2009). EEG coherence in children with attention-deficit/hyperactivity disorder and comorbid reading disabilities. *International Journal of Psychophysiology, 71*, 205–210.

Broyd, S. J., Demanuele, C., Debener, S., Helps, S. K., James, C. J., & Sonuga-Barke, W. J. (2009). Default-mode brain dysfunction in mental disorders: A systematic review. *Neuroscience and Biobehavioral Reviews, 33*, 279–296.

Chatrian, G. E., Lettich, E., & Nelson, P. L. (1985). Ten percent electrode system for topographic studies of spontaneous and evoked EEG activity. *American Journal of Electroneurodiagnostic Technology, 25*, 83–92.

Chen, J., Ros, T., & Gruzelier, J. H. (2013). Dynamic changes of ICA-derived EEG functional connectivity in the resting state. *Human Brain Mapping, 34*, 852–868.

Cheung, M. C., Chan, A. S., & Sze, S. L. (2009). Increased theta coherence during Chinese reading. *International Journal of Psychophysiology, 74*, 132–138.

Cheung, M. C., Chan, A. S., & Sze, S. L. (2010). Electrophysiological correlates of brand names. *Neuroscience Letters, 485*, 178–182.

Clarke, A. R., Barry, R. J., Heaven, P. C. L., McCarthy, R., Selikowitz, M., & Byrne, M. K. (2008). EEG coherence in adults with attention-deficit/hyperactivity disorder. *International Journal of Psychophysiology, 67*, 35–40.

Coben, R., Clarke, A. R., Hudspeth, W., & Barry, R. J. (2008). EEG power and coherence in autistic spectrum disorder. *Clinical Neurophysiology, 119*, 1002–1009.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates.

Crespo-Garcia, M., Pinal, D., Cantero, J. L., Díaz, F., & Zurrón, M. (2013). Working memory processes are mediated by local and long-range synchronization of alpha oscillations. *Journal of Cognitive Neuroscience, 25*, 1343–1357.

Damoiseaux, J. S., Rombouts, S. A., Barkhof, F., Scheltens, P., Stam, C. J., Smith, S. M., & Beckmann, C. F. (2006). Consistent resting-state networks across healthy subjects. *Proceedings of National Academy of Sciences USA, 103*, 13848–13853.

Dunn, B. R., & Reddix, M. D. (1991). Modal processing style differences in the recall of expository text and poetry. *Learning and Individual Differences, 3*, 265–293.

Dupuy, F. E., Clarke, A. R., Barry, R. J., McCarthy, R., & Selikowitz, M. (2008). EEG coherence in girls with attention-deficit/hyperactivity disorder: Stimulant effects in good responders. *International Journal of Psychophysiology, 70*, 151–157.

Fransson, P. (2005). Spontaneous low-frequency BOLD signal fluctuations: An fMRI investigation of the resting-state default mode of brain function hypothesis. *Human Brain Mapping, 26*, 15–29.

Fransson, P. (2006). How default is the default mode of brain function? Further evidence from intrinsic BOLD signal fluctuations. *Neuropsychologia, 44*, 2836–2845.

Freunberger, R., Fellinger, R., Sauseng, P., Gruber, W., & Klimesch, W. (2009). Dissociation between phase-locked and nonphase-locked alpha oscillations in a working memory task. *Human Brain Mapping, 30*, 3417–3425.

Freunberger, R., Klimesch, W., Griesmayr, B., Sauseng, P., & Gruber, W. (2008). Alpha, phase coupling reflects objects recognition. *Neuroimage, 42*, 928–935.

Gasser, T., Jennen-Steinmetz, C., & Verleger, R. (1987). EEG coherence at rest and during a visual task in two groups of children. *Electroencephalography and Clinical Neurophysiology, 67*, 151–158.

Greicius, M. D., Krasnow, B., Reiss, A. L., & Menon, V. (2003). Functional connectivity in the resting brain: A network analysis of the default mode hypothesis. *Proceedings of National Academy of Sciences USA, 100*, 253–258.

Haier, R. J., Neuchterlein, K. H., Hazlett, E., Wu, J. C., Peak, J., Browning, H. L., & Buchsbaum, M. S. (1988). Cortical glucose metabolic rate correlates of abstract reasoning and attention studied with positron emission tomography. *Intelligence, 12*, 199–217.

Haier, R. J., Siegel, B., Tang, C., Abel, L., & Buchsbaum, M. S. (1992). Intelligence and changes in regional cerebral glucose metabolic rate following learning. *Intelligence, 16*, 415–426.

Jann, K., Dierks, T., Boesch, C., Kottlow, M., Strik, W., & Koenig, T. (2009). BOLD correlates of EEG alpha phase-locking and the fMRI default mode network. *Neuroimage, 45*, 903–916.

Jausovec, N. (1996). Difference in EEG alpha activity related to giftness. *Intelligence, 23*, 159–173.

Jausovec, N. (2000). Differences in cognitive processes between gifted, intelligent, creative, and average individuals while solving complex problems: An EEG study. *Intelligence, 28*, 213–237.

Jausovec, N., & Jausovec, K. (2000). Differences in resting EEG related to ability. *Brain Topography, 12*, 259–273.

Jausovec, N., & Jausovec, K. (2003). Spatiotemporal brain activity related to intelligence: A low resolution brain electromagnetic tomography study. *Cognitive Brain Research, 16*, 267–272.

Jausovec, N., & Jausovec, K. (2008). Spatial rotation and recognizing emotions: Gender related differences in brain activity. *Intelligence, 36*, 383–393.

Kirov, R., Weiss, C., Siebner, H. R., Born, J., & Marshall, L. (2009). Slow oscillation electrical brain stimulation during waking promotes EEG theta activity and memory encoding. *Proceedings of National Academy of Sciences USA, 106*, 15460–15465.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Research Reviews, 29*, 169–195.

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition-timing hypothesis. *Brain Research Reviews, 53*, 63–88.

Leisman, G., & Ashkenazi, M. (1980). Aetiological factors in dyslexia. *Neuroscience, 11*, 157–164.

McKay, M. T., Fischler, I., & Dunn, R. R. (2003). Cognitive style and recall of text: An EEG analysis. *Learning and Individual Differences, 14*, 1–21.

Marosi, E., Harmony, T., Becker, J., Reyes, A., Bernal, J., Fernández, T., … Guerrero, V. (1995). Electroencephalographic coherences discriminate between children with different pedagogical evaluation. *International Journal of Psychophysiology, 19*, 23–32.

Marosi, E., Harmony, T., Sánchez, L., Becker, J., Bernal, J., Reyes, A., … Fernández, T. (1992). Maturation of the coherence of EEG activity in normal and learning-disabled children. *Electroencephalography and Clinical Neurophysiology, 83*, 350–357.

Mima, T., Oluwatimilehin, T., Hiroak, T., & Hallet, M. (2001). Transient interhemispheric neural synchrony correlates with object recognition. *Journal of Neuroscience, 21*, 3942–3948.

Neubauer, A. C., & Fink, A. (2009). Intelligence and neural efficiency. *Neuroscience and Biobehavioral Reviews, 33*, 1004–1023.

Palva, S., & Palva, J. M. (2007). New vision for alpha-frequency band oscillations. *Trends in Neuroscience, 30*, 150–158.

Palva, S., & Palva, J. M. (2011). Functional role of alpha-band phase synchronization in local and large-scale cortical networks. *Frontiers in Psychology, 2*, 204. doi: 10.3389/fpsyg.2011.00204

Petsche, H. (1997). EEG coherence and mental activity. In F. Angeleri, S. Butler, S. Giaquinto, & J. Majakowski (Eds.), *Analysis of the electrical activity of the brain* (pp. 141–168). Chichester, UK: John Wiley and Sons Ltd.

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of National Academy of Sciences USA, 98*, 676–682.

Sauseng, P., Hoppe, J., Klimesch, W., Gerloff, C., & Hummel, F. C. (2007). Dissociation of sustained attention from central executive functions: Local activity and interregional connectivity in the theta range. *European Journal of Neuroscience, 25*, 587–593.

Schmid, R. G., Tirsch, W. S., Rappelsberger, P., Weinmann, H. M., & Pöppl, S. J. (1992). Comparative coherence studies in healthy volunteers and Down's syndrome patients from childhood to adult age. *Electroencephalography and Clinical Neurophysiology, 83*, 112–123.

Thatcher, R. W., Krause, P. J., & Hrybyk, M. (1986). Cortico-cortical associations and EEG coherence: A two-compartmental model. *Electroencephalography and Clinical Neurophysiology, 64*, 123–143.

Thatcher, R. W., McAlaster, R., Lester, M. L., Horst, R. L., & Cantor, D. S. (1983). Hemispheric EEG asymmetries related to cognitive functioning in children. In A. Perecuman (Ed.), *Cognitive processing in the right hemisphere* (pp. 125–146). Orlando, FL: Academic Press.

Thatcher, R. W., North, D., & Biver, C. (2005). EEG and intelligence: Relation between EEG coherence, EEG phase delay and power. *Clinical Neurophysiology, 116*, 2129–2141.

Thatcher, R. W., North, D. M., & Biver, C. (2008). Development of cortical connections as measured by EEG coherence and phase delays. *Human Brain Mapping, 29*, 1400–1415.

Thatcher, R. W., & Walker, R. A. (1985). EEG coherence and intelligence in children. *Electroencephalography and Clinical Neurophysiology, 61*, S161.

van den Heuvel, M. P., & Hulshoff Pol, H. E. (2010). Exploring the brain network: A review on resting-state fMRI functional connectivity. *European Neuropsychopharmacology, 20*, 519–534.

Varela, F. J., Lachaux, J. P., Rodriguez, E., & Martinerie, J. (2001). The brainweb: Phase synchronization and large-scale integration. *Nature Reviews Neuroscience, 2*, 229–238.

Weiss, S., & Mueller, H. M. (2003). The contribution of EEG coherence to the investigation of language. *Brain and Language, 85*, 325–343.

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