Creativity Research Journal

ISSN: 1040-0419 (Print) 1532-6934 (Online) Journal homepage: http://www.tandfonline.com/loi/hcrj20

Different Brain Wave Patterns and Cortical Control Abilities in Relation to Different Creative Potentials

Ying-Han Li, Chao-Yuan Tseng, Arthur Chih-Hsin Tsai, Andrew Chih-Wei Huang & Wei-Lun Lin

To cite this article: Ying-Han Li, Chao-Yuan Tseng, Arthur Chih-Hsin Tsai, Andrew Chih-Wei Huang & Wei-Lun Lin (2016) Different Brain Wave Patterns and Cortical Control Abilities in Relation to Different Creative Potentials, Creativity Research Journal, 28:1, 89-98, DOI: 10.1080/10400419.2016.1125255

To link to this article: http://dx.doi.org/10.1080/10400419.2016.1125255

Published online: 22 Feb 2016.

CREATIVITY RESEARCH JOURNAL, *28*(1), 89–98, 2016

ISSN: 1040-0419 print/1532-6934 online
DOI: 10.1080/10400419.2016.1125255

Different Brain Wave Patterns and Cortical Control Abilities in Relation to Different Creative Potentials

Ying-Han Li and Chao-Yuan Tseng
Department of Psychology, Fo Guang University, Yilan, Taiwan

Arthur Chih-Hsin Tsai
Institute of Statistical Science, Academia Sinica, Taipei, Taiwan

Andrew Chih-Wei Huang and Wei-Lun Lin
Department of Psychology, Fo Guang University, Yilan, Taiwan

Contemporary understanding of brain functions provides a way to probe into the mystery of creativity. However, the prior evidence regarding the relationship between creativity and brain wave patterns reveals inconsistent conclusions. One possible reason might be that the means of selecting creative individuals in the past has varied in each study. By distinguishing creative potential as open-ended versus closed-ended based on theoretical views, this study examined different brain wave patterns and cortical control abilities in relation to different creative potentials by using electroencephalogram (EEG) biofeedback equipment. The results demonstrated that participants' performance on the open-ended creative problem was positively related to EEG alpha frequencies, whereas performance on the closed-ended creative problem was related to larger variability in EEG dynamics between alpha and beta waves when performing either open-ended or closed-ended creativity tasks. Further, better control in changing states of brain wave activities according to the EEG biofeedback signals could predict closed-ended creativity performance. Open-ended creativity was related only to the enhancement of alpha signals. These results help clarify previous inconsistent findings, reveal different natures of distinct creativities, and further suggest ways to improve different aspects of creativity with modified biofeedback procedures.

Research has been conducted through various means and sought to understand the mysterious concept of creativity for many decades. With the advantages of neurocognitive techniques, it is pointed out that any cognitive theories should cooperate with neurocognitive evidence, including creativity (Dietrich, 2004; Pfenninger & Shubik, 2001). A variety of psychophysiological measurement methods have therefore been employed, including electroencephalogram (EEG), positron emission tomography (PET), near-infrared spectroscopy (NIRS), and functional magnetic resonance imaging (fMRI; for a review, see Dietrich & Kanso, 2010).

One of the interesting issues is to determine the relationship between creativity and brain wave patterns by using EEG equipment. However, past research has shown incongruent results. Many found the link between creativity and alpha (α) brain wave activation (e.g., Fink et al., 2009a), but others did not (e.g., Razumnikova, 2007). In addition, Martindale (1999) has proposed that creative individuals might exhibit higher variation of brain wave patterns and, hence, cortical control abilities. However, the notion has not gained empirical support (Martindale & Armstrong, 1974). One possibility of the inconsistency might stem from researchers' methods of

Address correspondence to Wei-Lun Lin, Department of Psychology, Fo Guang University, Taiwan, No.160, Linwei Rd., Jiaosi Shiang, Yilan County, 26247, Taiwan, E-mail: wllin.fgu@gmail.com

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/HCRJ.

selecting creative individuals, which varied in each study. Theories and accumulated evidence have shown that different creativity measures involve distinct mental processes and correlate with different psychological factors (e.g., Lin & Lien, 2013; Lin, Hsu, Chen, & Wang, 2012). Therefore, this study distinguished two types of creative potential: open-ended and closed-ended. Their different relationships with brain wave patterns and cortical control abilities were then explored.

CREATIVITY AND CORTICAL ACTIVITY

Kris (1952) proposed that creative individuals have easier access to a freely associative, unconscious, and imaginative primary thinking mode, which can enable them to produce more novel ideas. This thinking mode is more likely to occur in hypnogogic or reverie states and is related to alpha brain wave activation (Lindsley, 1960; von Stein & Sarnthein, 2000). Thereafter, Martindale (1999) developed the low-arousal hypothesis, suggesting the link between creativity and low cortical arousal (i.e., high alpha power). Recent neurological studies have also demonstrated that slower brain wave rhythms carry information over long-distance, distributed connections (e.g., Varela, Lachaux, Rodriguez, & Martinerie, 2001), which allows remote and creative associations (Gruzelier et al., 2014).

Accordingly, many studies have investigated the relationship between creativity and alpha waves and have gained some support (Fink & Neubauer, 2006; Fink, Grabner, Benedek, & Neubauer, 2006; Grabner, Fink, & Neubauer, 2007; Jaušovec, 2000; Martindale, 1999; Mölle et al., 1996). For example, higher increases in alpha power were discovered in the prefrontal lobes of professional dancers during a dance improvisation (Fink, Graif, & Neubauer, 2009b). Participants significantly revealed elevated alpha activation when they were doing free-association creative tasks (Fink et al., 2009a) or were generating original responses for alternate-use tasks (Jauk, Benedek, & Neubauer, 2012). In addition, participants showed increasing creativity when they had received relaxation-response training in alpha brain wave production (Foster, 1990); moreover, participants were able to increase alpha wave activation in their frontal cortexes after 2 weeks' training in divergent thinking (Fink et al., 2006). Furthermore, self-administered high-dose alcohol consumption was found to decrease prefrontal activity (i.e., low cortical arousal), facilitate regression to primary thinking mode, and increase original responses (for a review, see Svensson, Archer, & Norlander, 2006). This evidence strengthens the link between creativity and alpha waves.

However, some inconsistencies exist (for a review, see Dietrich & Kanso, 2010). When comparing high- and low-creativity participants, some researchers found no correlation between creativity performance and EEG alpha-band activation (Martindale & Hasenfus, 1978). Razumnikova (2007) further found that participants doing the remote association test (RAT; Mednick & Mednick, 1967) exhibited increasing beta (β) power compared with those who completed the simple association test, in which beta wave activation is considered to reflect an abstract, logical, and reality-oriented secondary thinking mode (Kris, 1952; Martindale, 1999).

CREATIVITY, VARIATION IN BRAIN WAVE PATTERNS, AND CORTICAL CONTROL

Past studies have found that each stage of the creative process has featured dissimilar patterns of brain wave activation (e.g., Jaušovec, 1997; Martindale & Hasenfus, 1978; Norlander & Gustafson, 1998). For example, more alpha wave activation was found and alcohol intake better facilitated creativity during the incubation and illumination phases than during the preparation and verification phases when participants were solving creative problems (Jaušovec, 1997; Norlander & Gustafson, 1998). In addition, the result—highly creative individuals exhibited more alpha indices during creative inspiration—could occur only when these participants were asked to be creative (Martindale & Hasenfus, 1978). It was thus proposed that creative individuals exhibit higher variation of brain wave patterns or frontal flexibility to switch between different processing modes (Jauk et al., 2012). This might be attributed to their cortical control abilities (Martindale, 1999).

Martindale and Armstrong (1974) tested this operant control hypothesis with an EEG biofeedback device. They asked selected high- and low-creativity participants to control their own mental status to make a signal tone appear or disappear, which corresponds to the detection of alpha wave activation. However, supportive evidence was not obtained, and it was concluded that high-creativity individuals did not exhibit better cortical control abilities than low-creativity individuals (Martindale, 1999; Martindale & Armstrong, 1974).

DISTINCTION BETWEEN OPEN-ENDED CREATIVITY AND CLOSED-ENDED CREATIVITY

As reviewed previously, past studies compared different brain wave patterns or cortical control abilities between high- and low-creativity individuals, but achieved inconsistent results. Importantly, past studies rarely considered the ways in which differentiation between high- and low-creativity individuals varies; for instance, in Martindale and Armstrong's study (1974), the researchers averaged the participants' scores on divergent thinking test and RAT measures even though the two measures were not correlated in their own report. It has been pointed out that creativity measures should be further distinguished because they might involve distinct brain circuits (Dietrich, 2004). In particular, an open-ended creative problem (such as a divergent thinking problem, which requires participants to list as many uses of an object as possible) and a closed-ended creative problem (such as the RAT, which asks for a correct answer to find a common concept of three presented items) included different task demands (Wakefield, 1989), and they might involve different processes (Lin & Lien, 2013; Lin et al., 2012). The two measures should be separately addressed.

The dual process account of creativity (Lin & Lien, 2013; Lin et al., 2012) has recently been proposed; it refers to the different processes in each kind of creativity. Incorporated with primary-secondary thinking mode theory (Kris, 1952; Noy, 1969; Suler, 1980) and dual process theories (e.g., Evans, 2003, 2007; Sloman, 1996; Stanovich & West, 2000), where associative System 1 is analogous to the primary thinking mode and evaluative System 2 is analogous to the secondary thinking mode, Lin et al. (2012, 2013) inferred that an open-ended creativity task mainly relies on System 1 processing when the task is to generate as many diverse ideas as possible. On the other hand, a closed-ended creativity task requires processing in both systems 1 and 2 to generate novel ideas and alternatively evaluate their appropriateness when a correct final answer is requested. Empirical evidence indicates that individuals' performance on open-ended and closed-ended tasks did not correlate with each other (e.g., Lin & Lien, 2013) and that various psychological factors, such as working memory (Lin & Lien, 2013), personality traits and gender (Lin et al., 2012), and emotional state (Lin, Tsai, Lin, & Chen, 2014) correlated differently with these two measures. In view of this, whether different brain wave patterns or cortical control abilities are requested for open-ended and closed-ended creative problem solving is an interesting issue to explore.

RESEARCH PURPOSES AND HYPOTHESES

In this study, the brain wave patterns of participants who were performing either open-ended or closed-ended creativity tasks were investigated in Study 1A. The abilities of cortical control in relation to different creative performances were afterwards examined in Study 1B. Based on the dual process account of creativity (Lin & Lien, 2013; Lin et al., 2012) and the notions of Lindsley (1960) and Martindale (1999), better performance on the open-ended creativity task was expected to be more strongly related to alpha waves, as a good performance on this task relies mainly on associative System 1 processing, which is related to low cortical activation, to generate diverse ideas. On the other hand, better performance on the closed-ended creativity task would demonstrate a transformation between alpha and beta waves, as the task demands shifts between Systems 1 and 2 to achieve a novel and appropriate correct answer. Accordingly, individuals with high closed-ended creativity potential might exhibit better cortical control abilities to transform their brain wave patterns.

STUDY 1A

Method

Screening Procedure

To expend the variance of creative performances and increase representativeness of participants with different creative potentials, participants in Study 1A were first screened from 111 Fo Guang University students (*M* age = 19.03, *SD* = 0.98, age range = 18–22; 45% women; to earn course credit). These 111 participants performed both an open-ended divergent thinking test (The Chinese Version of Creative Thinking Test [CVCTT], Wu, 1998) and a closed-ended insight problem task (10 pure insight problems, Lin et al., 2012). The CVCTT consists of typical divergent thinking problems (i.e., unusual uses and figure completion) designed from subtests of the Torrance Test of Creative Thinking (TTCT; Torrance, 1974) with culturally familiar materials. The instrument was developed from a large-sample norm in Taiwan that included elementary to graduate students and has established stable reliability and validity results. The 10 pure-insight problems that necessarily require a reconstructing process, as suggested by Weisberg (1995), consist of five verbal and five figural problems. Cronbach's alpha coefficient for the task was .68.

According to their performances, participants in the top one-third and the bottom one-third on the CVCTT (both verbal and figural subtests), in addition to average performance on the insight problem task, were selected as an open-ended creativity group (*n* = 16). The screening criterion for the closed-ended creativity group (*n* = 19) was analogous, except the former test performance was according to the insight problem-solving task and the latter was according to the CVCTT.

Participants and Design

Thirty-five participants (*M* age = 19.71, *SD* = 1.23, age range = 18–22; 43% women) were paid to participate in Study 1A. All were healthy and right-handed. The open-ended creativity group was asked to solve an open-ended Chinese version of free association tests (CFAT) and the closed-ended creativity group was asked to solve the closed-ended Chinese Remote Association Test (CRAT; Jen, Chen, Lien, & Cho, 2004) while the physiological measurement was underway. The study was approved by the Ethics Committee of Department of Psychology, Fo Guang University. All participants signed an informed consent form before the experiment.

Two Types of Creativity Measures

The CFAT and CRAT were short formed and suitable for measuring EEG data. The two tasks were also displayed by a similar stimulus representation and procedure.

Open-ended CFAT. In CFAT, participants were given a target word of two Chinese characters, such as *the ocean*, to freely associate between the connected concepts as much as they were able to. A total of 15 target words were selected from the associative norming lists established by Chen (1999). According to the norm, the originality index for each problem was scored and summed. Responses that occurred in less than 2% of the norm scored 2. Responses between 2% and 4.99% of the norm scored 1. Finally, responses that occurred more than 5% of the norm scored 0.

Closed-ended CRAT. Fifteen CRAT problems from Jen et al. (2004) were used. Based on Mednick's (1962) original RAT, the CRAT problems required solvers to identify a target Chinese character that could, respectively, link the three presented Chinese characters to make three two-character Chinese words. The total correctness of the 15 problems was counted as the index.

Apparatus and Procedure

This study adopted the EEG biofeedback apparatus with the ProComp Infiniti System (2003), developed by Thought Technology Ltd., Canada. The use of EEG biofeedback equipment allows for the measurement of brain wave patterns and other physiological indices (only the brain wave data were reported in the present study). In addition, biofeedback signals were provided by the equipment in Study 1B.

All signals were delivered to a personal computer and analyzed with Biofeedback Multimedia Software (BioGraph Infiniti 5.0), which was designed to set up the program. According to the International 10–20 System, the monopolar EEG electrodes were placed at prefrontal Fp1 and Fp2 because previous work demonstrated a close link between brain wave differences in the frontal lobe and creativity (e.g., Fink et al., 2009b), and the frontal lobe was considered an important base of creativity (e.g., Dietrich, 2004). The EEG signals of Fp1 and Fp2 were sampled at 2048 Hz. In addition, eye-induced artefacts were recorded bipolarly by two eye channels (vertical VEOG and horizontal HEOG), and the EEG signals were sampled at 256 Hz. All of the EEG channels above were measured with the ipsilateral ear (A1 or A2) as the reference.

Participants were tested alone in a small room and sat down in a comfortable chair in front of a screen. Participants were first given 3 min to relax and were instructed to refrain from eye or other movements until the end of the experiment. They then received a total of 15 trials, each of which included a 4-sec blank screen, a 3-sec fixation cross, and a following problem presentation with 1 min to solve the problem. Participants who were assigned to solve the CFAT (the open-ended creativity group) viewed a two-character word, whereas participants assigned to solve the CRAT (the closed-ended creativity group) viewed three characters. Participants could only report their answer after the time limit of each trial; in the meantime, their answers were recorded and the EEG recording was paused until the next trial. The one-trial procedure is presented in Figure 1. The whole procedure took approximately 40 min.

Analysis of EEG Cortical Oscillatory Changes

In this study, the preprocessing of each participant's data was performed by using the scripting and EEGLAB command line functions (Delorme & Makeig, 2004). Signals were filtered by using a finite impulse response (FIR) filter (eegfilt; EEGLAB) with a band pass from 1 to 50 Hz. Data epochs were extracted from 5.0 to 35 sec after problem-solving onsets to exclude the transient responses to the stimulus onset. Individuals' EEG activity during the middle two seconds of each blank screen phase was assessed as the baseline of each trial (see also Figure 1). The extended infomax independent component analysis (ICA) algorithm (Jung et al., 2001; Lee, Girolami, & Sejnowski, 1999) was then applied to all four scalp-channel signals across 15 concatenated epochs. Independent components accounting for eye-movement artifacts were identified and removed for the further calculation of indices of frequencies.

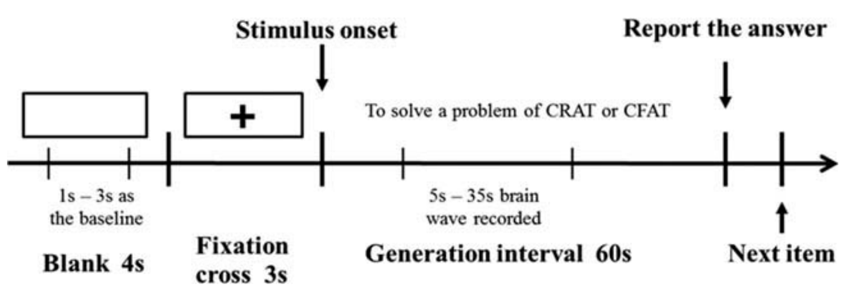

FIGURE 1 Schematic time course and analysis procedures of the experimental tasks in Study 1A.

The single-trial event-related spectral perturbation (ERSP; Makeig, 1993) of the rest of the components was then analyzed. Three indices were extracted: the alpha (7–13 Hz) and the beta (13–30 Hz) oscillations were analyzed by detecting their appearances at levels above 5 μV with a time of 0.25 ms. The third index—the number of transformations between alpha and beta waves—was conducted by the summed frequencies detected in two situations: a decrease in alpha accompanies an increase in beta, and a decrease in beta accompanies an increase in alpha.

Results

To investigate whether the three brain wave indices contributed differently to different creativity measures, two correlational and two regression analyses were computed separately on the performances of the open-ended and closed-ended creativity groups. The results showed that the Pearson's *r*s of alpha, beta, and transformation between alpha and beta frequencies to open-ended CFAT performances were .49 (p = .027), .13 (p = .32), and .40 (p = .06). The correlations between the above three indices with closed-ended CRAT performances were .26 (p = .15), .30 (p = .10), and .36 (p = .06). The alpha frequencies most significantly correlated to open-ended creativity performance, and the transformation between alpha and beta most correlated to closed-ended creativity performance at a marginally significant level.

In simultaneous-entry regression analyses, three brain wave indices were computed as predictive variables and the performances on the two creativity measures were considered dependent variables. The results demonstrated that the β values of alpha and beta, as well as the transformation between alpha and beta on the open-ended CFAT performances were .40, –.18, and .19. The β values of the three indices on closed-ended CRAT performances were –.24, .14, and .50. Although these results revealed trends compatible with predictions, the *p*s did not reach a significant level.

These trends highlighted some further analyses. Similar to previous studies (e.g., Mölle, Marshall, Wolf, Fehm, & Born, 1999), the median splits according to participants' performance on the open-ended CFAT and the closed-ended CRAT were computed separately for the two groups. Participants scored higher on the CFAT (M = 25.96, SD = 0.63) denoted as OP (open-ended problem)-high subgroup (n = 8), as compared to the OP-low subgroup (n = 8), which scored lower on the task (M = 22.76, SD = 1.4, $t(14)$ = 5.88, p < .001, d = 2.94). Participants scored higher on the CRAT (M = 9.9, SD = 0.99), denoted as CP (closed-ended problem)-high subgroup (n = 10), as compared to CP-low subgroup (n = 9), which scored lower on the task (M = 6.67, SD = 1.22, $t(17)$ = 6.35, p < .001, d = 2.92). Independent *t*-tests (all one-tailed tests) were respectively conducted with the three brain wave indices for OP-high versus OP-low subgroups and CP-high versus CP-low subgroups. The results showed that participants in the OP-high subgroup only had significantly more α frequencies (M = 27.56, SD = 4.07) than those in the OP-low subgroup (M = 22.9, SD = 5.28), $t(14)$ = 1.98, p = .034, d = 0.99. On the other hand, the CP-high subgroup not only exhibited more α frequencies than the CP-low subgroup (M = 24.27, SD = 5.16 vs. M = 19.84, SD = 4.24, $t(17)$ = 2.03, p = .025, d = 0.93), but it additionally transformed more between α and β than the CP-low subgroup (M = 19.78, SD = 4.18 vs. M = 15.74, SD = 3.58, $t(17)$ = 2.25, p = .019, d = 1.03).

Discussion

The results of Study 1A showed that good performances on the open-ended creativity measure related more to alpha brain wave activation and good performances on the closed-ended creativity measure related more to transformations between alpha and beta. Given that open-ended and closed-ended creative problem solving include different task demands (Wakefield, 1989) and involve distinct processes (Lin & Lien, 2013; Lin et al., 2012), says, the former involves mainly System 1 processing and the latter involves alternating use of System 1 and 2 processing, the differences in brain wave activities were demonstrated when these two measures were separated.

Some criticisms might arise because the CFAT and the CRAT adopted in this study were simply distinguished as open-ended and closed-ended. RAT was associative in nature and creativity tasks represent a continuum ranging from open to closed-ended (Acar & Runco, 2014; Benedek, Könen, & Neubauer, 2012). However, empirical evidence found that RAT is more strongly correlated to convergent thinking and it was referred to as a convergent creative problem-solving task by Jones, Caulfield, Wilkinson, and Weller (2011). Given its task demands that participants find the only correct answer, CRAT was considered more characteristic of a closed-ended task in the present study, compared to the CFAT, in which correct answers were not requested.

Probably because of a small sample size in each group, the regression analyses did not show significant results in Study 1A. In addition, there was a marginal correlation between open-ended CFAT performances and transformation between alpha and beta (although the relationship did not show in the follow-up regression and *t*-test analyses). If individuals with different creative potential exhibit distinct brain wave patterns while they are performing creativity tasks, it is possible that they have different cortical control abilities. Individuals who are good at closed-ended creativity might have better cortical control to switch between alpha and beta, while individuals good at open-ended creativity might not. If these results can be found, they can strengthen the findings in Study 1A. In Study 1B, participants were asked to proceed to a different procedure: a cortical control experiment using the EEG biofeedback equipment, which was based on Martindale and Armstrong's method (1974) but distinguished between different creativities.

STUDY 1B

Method

Participants

The same 35 participants in Study 1A were recruited to perform the cortical control task in Study 1B.

Apparatus and Procedures

The same EEG biofeedback equipment in Study 1A was used; however, it presented a biofeedback signal in Study 1B. The experiment started with an adaptation trial. For 180 seconds, participants were asked to relax and were instructed to refrain from unnecessary movements until the end of the experiment. The following baseline recording lasted 250 sec. The third habituation trial, lasting 50 sec, allowed participants to get acquainted with the biofeedback 400 Hz signal tone. Participants then proceeded to a 150-sec practice trial in which they were told that the tone would come on when they were in certain mental states, and they were asked to practice making the tone turn on or off. The signal tone would be given when alpha activation was detected with levels above 5 μV and lasted for 0.25 ms. After that, two of the alpha enhancement trials and the other two of alpha suppression trials followed, each of which lasted 150 sec. During the alpha enhancement trial, participants were asked to make the sound occur as often as possible. They were asked to prevent the sound as much as possible, however, during the alpha suppression trial. The frequencies of the signal tones (and, hence, the alpha wave frequencies) were recorded during the alpha enhancement and suppression trials. The whole procedure is presented in Figure 2, and it took approximately 30 min.

Analysis of Dependent Variables

Three indices were computed as dependent variables. The first two were the mean ratio of alpha during the two enhancement trials and two suppression trials. The ratio of alpha was computed from the alpha frequency during the test phase divided by the baseline alpha frequency. The third index, cortical control ability, subtracted the suppression trial's mean ratio of alpha from the enhancement trial's mean ratio of alpha. It indicates the degree to which an individual can increase or decrease his or her alpha activity in accordance with the instructions. The larger the extent, the better his/her cortical control ability.

Results

As in Study 1A, two correlational and two regression analyses were computed separately on the three indices of cortical control task and participants' former performances of open-ended or closed-ended creativity tasks. The results showed that the Pearson's *r*s of the ratio of alpha on the enhancement trial, the suppression trial, and cortical control index to open-ended CFAT performances were .35 (p = .09), .29 (p = .13), and –.05 (p = .42). The correlations between the above three indices with closed-ended CRAT performances were .31 (p = .10), -.01 (p = .49), and .52 (p = .01). The ratio of alpha on the enhancement trial marginally correlated to the open-ended creativity performance, while the cortical control ability was significantly correlated to the closed-ended creativity performance.

In simultaneous-entry regression analyses, three indices of the cortical control task were computed as predictive variables and performances on two creativity measures were computed as dependent variables. The results demonstrated that the β values of the ratio of alpha on the enhancement trial and the cortical control index on open-ended CFAT performances were .36 and –.07 (the ratio of alpha on the suppression trial was excluded from the model). No β values were statistically significant. On the other hand, the β values of the ratio of alpha on the suppression trial and the cortical control index (the ratio of alpha on the enhancement trial was excluded from the model) on closed-ended CRAT performances were –.02 and .52, $t(16)$ = 2.43, p = .03.

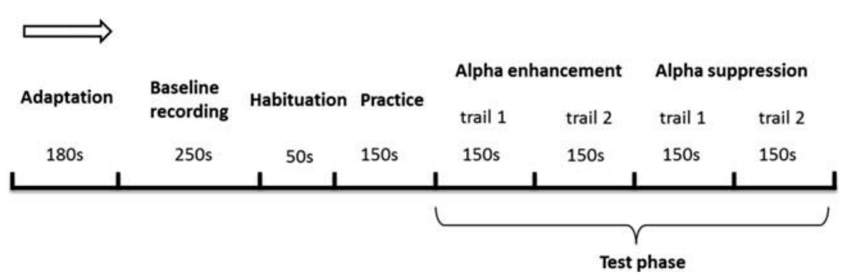

FIGURE 2 The cortical control procedure in Study 1B.

These results indicated that better performance on the closed-ended creativity task was predicted by better cortical control ability, while performance on the open-ended creativity task did not.

As in Martindale and Armstrong (1974), the analyses comparing high and low creatives were also computed. With the same median split as in Study 1A, the results showed that the OP-high subgroup exhibited significantly more alpha ratio (M = 1.64, SD = 0.63) on the enhancement trial compared to the OP-low subgroup (M = 1.13, SD = 0.45), $t(14)$ = 1.83, p = .044, d = 0.92. Although not significant, there was a trend of more alpha frequency for the OP-high subgroup (1.55 ± 1.06 vs. 1.01 ± 0.35, p = .09) on the alpha suppression trial. The two subgroups did not differ in the cortical control index. On the other hand, the CP-high subgroup (M = 0.47, SD = 0.47) exhibited a significantly higher cortical control index than the contrasted CP-low subgroup (M = 0.1, SD = 0.25), $t(17)$ = 2.12, p = .025, d = 0.97. The other two indices were not different.

Discussion

The results of Study 1B showed that individuals' higher cortical control abilities predicted their better performances on the closed-ended creativity task. They could flexibly make the EEG biofeedback signals present or absent, which indicated the appearance or disappearance of alpha brain waves and, supposedly, System 1 or System 2 processing. On the other hand, individuals' open-ended creativity performances were more related to alpha appearance on the enhancement trial. Interestingly, those who performed well on the open-ended creativity task even exhibited more alpha activation than their own baseline conditions under the suppression condition (mean ratio of the alpha equals 1.55 for the OP-high subgroup). They might be only capable of increasing alpha activities. These results could lend support to the findings in Study 1A that different creativities were related to different brain wave activation patterns and help explain why individual performances on the open-ended versus closed-ended creative problem solving were not correlated (Lin & Lien, 2013).

GENERAL DISCUSSION AND CONCLUSION

Although previous researchers have suggested that different creativity measures include different task demands (Wakefield, 1989) and might involve distinct brain circuits (Dietrich, 2004), past studies rarely compared, say, open-ended versus closed-ended creativity, in one study in the domain of EEG research. In addition, the frontal flexibility index of brainwave transformation between alpha and beta, based on the theoretical accounts of creative processes (Jauk et al., 2012; Kris, 1952; Lin & Lien, 2013; Lin et al., 2012), was first developed in this study, and the controllability of this flexibility was also examined. The results of this study demonstrate that different brain wave patterns and cortical control abilities correlated with different creativity performances. Open-ended creativity was related to more alpha activation, whereas closed-ended creativity involved more transformations between alpha and beta, which the participants could voluntarily control. These findings may offer the dual process account of creativity (Lin & Lien, 2013; Lin et al., 2012) a physiological support that different types of creativity involve different processes. Open-ended creative problem solving relies mainly on System 1 processing or primary thinking mode, as indicated by cortical deactivation; and, hence, alpha wave activation (Martindale, 1999; Pfurtscheller, Stancák, & Neuper, 1996). Closed-ended creative problem solving involves both System 1 and 2 processing and entails a higher variation of brain wave patterns and frontal flexibility (Jauk et al., 2012).

Recent studies have revealed more functions of alpha synchronization, such as inhibition of task-irrelevant processes and retention of relevant information in working memory (for a review, see Klimesch, Sauseng, & Hanslmayr, 2007). Beta rhythm was also proposed as a binding mechanism that integrates various sources of information (Schnitzler & Gross, 2005). These processes might also contribute to creative cognition, respectively. Because idea generation is needed for both open- and closed-ended creative problem solving, the internal retention of information and inhibition of irrelevant stimuli that allow representations of associations or ideas are important for both kinds of creativity. However, it might be more crucial to integrate or select proper answers from various associates for a closed-ended problem.

This distinction between open-ended and closed-ended creativities can help clarify the various and inconsistent results obtained in previous studies. For example, the findings that performing RAT tasks revealed higher beta power might be attributable to the greater involvement of System 2 or integration processing (and hence beta waves) in a closed-ended RAT task, rather than in an open-ended free association task (Razumnikova, 2007). Furthermore, reexamining the operant control hypothesis (Martindale & Armstrong, 1974; Martindale, 1999) under this distinction showed that highly creative individuals did exhibit better cortical control abilities, but only if they were superior at closed-ended creativity. Thus, the previous low-arousal-hypothesis (Martindale, 1999) that proposed the simple link between creativity and low cortical arousal should be extended according to distinct creativity measures.

The EEG-biofeedback training has recently been applied to increase individuals' abilities in various domains, such as attention (Egner & Gruzelier, 2004), memory (Vernon et al., 2003), music (Gruzelier et al., 2014), and dance performance (Raymond, Sajid, Parkinson, & Gruzelier, 2005). With respect to creativity, a few studies explored EEG-biofeedback training on divergent thinking abilities but obtained inconsistent results (Boynton, 2001; Doppelmayr & Weber, 2011). No published study has tried to increase closed-ended creative performance with EEG-biofeedback equipment. The results of this study, which showed that open-ended creativity was related only to alpha enhancement feedback whereas closed-ended creativity was related to both alpha enhancement and suppression, suggest ways to improve different aspects of creativity with distinct EEG-biofeedback procedures. In addition, previous research has indicated differences between artistic and scientific creativity (e.g., Simonton, 2008; Stent, 2001) and has suggested that open-ended and closed-ended creativity were analogues for the fundamental distinction between them (Lin & Lien, 2013; Lin et al., 2012). Whether artists and scientists exhibit different brain wave patterns or distinct cortical control abilities, and how to improve different creative achievements through EEG-biofeedback training, are interesting issues worth further investigation.

There are some limitations in this study. The first concerns the sample size; further research with a larger sample size might be needed. However, the participants in this study were screened from a large sample and could be considered representative. In addition, the magnitudes of the statistical results were of medium to large effect size, as defined by Cohen (1992). Second, with the restriction to a few EEG electrodes of biofeedback equipment, some issues such as hemispheric lateralization, different alpha bands, and different cortical areas in relation to different creativity measures were not explored in the present study. Some previous studies have found that creativity is more related to right hemisphere activation (e.g., Gibson, Folley, & Park, 2009; Jung et al., 2009), but others failed to observe the phenomena (e.g., Fink et al., 2009a; Goel & Vartanian, 2005). The different relationships of the upper alpha band (10.1–12.9 Hz) and lower alpha band (7.9–10.1 Hz) to creativity were investigated, but obtained inconsistent results (e.g., Fink, Schwab, & Papousek, 2011; Grabner et al., 2007; Jauk et al., 2012; Razumnikova, Volf, & Tarasova, 2009). Furthermore, more alpha activation has also been found in different cortical areas, such as parietal cortical areas (Jauk et al., 2012) and temporal and occipital areas (Fink et al., 2011). Further research could explore these issues while distinguishing different creativity measures.

In sum, this exploratory study demonstrates distinct brain wave patterns and cortical control abilities in relation to different creativities. It helps to understand previous inconsistent results, reveals distinct natures of different creativities, and suggests issues for future exploration.

ACKNOWLEDGMENTS

This research was supported by grants to the corresponding author from the National Science Council of Taiwan (NSC 98-2410-H-431-006).

REFERENCES

Acar, S., & Runco, M. A. (2014). Assessing associative distance among ideas elicited by tests of divergent thinking. *Creativity Research Journal*, *26*, 229–238. doi:10.1080/10400419.2014.901095

Benedek, M., Könen, T., & Neubauer, A. C. (2012). Associative abilities underlying creativity. *Psychology of Aesthetics, Creativity, and the Arts*, *6*, 273–281. doi:10.1037/a0027059

Boynton, T. (2001). Applied research using alpha/theta training for enhancing creativity and well-being. *Journal of Neurotherapy*, *5*, 5–18. doi:10.1300/J184v05n01_02

Chen, H. C. (1999). *Cognition and metacognition: The establishment of associative norming lists of Chinese words* Report No. NSC 87-2418-H-030-006). Taipei, Taiwan: National Science Council Funding Research Project.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*, 155–159. doi:10.1037/0033-2909.112.1.155

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*, 9–21. doi:10.1016/j.jneumeth.2003.10.009

Dietrich, A. (2004). The cognitive neuroscience of creativity. *Psychonomic Bulletin & Review*, *11*, 1011–1026. doi:10.3758/BF03196731

Dietrich, A., & Kanso, R. (2010). A review of EEG, ERP, and neuroimaging studies of creativity and insight. *Psychological Bulletin*, *136*, 822–848. doi:10.1037/a0019749

Doppelmayr, M., & Weber, E. (2011). Effects of SMR and theta/beta neurofeedback on reaction times, spatial abilities, and creativity. *Journal of Neurotherapy*, *15*, 115–129. doi:10.1080/10874208.2011.570689

Egner, T., & Gruzelier, J. H. (2004). EEG Biofeedback of low beta band components: Frequency-specific effects on variables of attention and event-related brain potentials. *Clinical Neurophysiology*, *115*, 131–139. doi:10.1016/S1388-2457(03)00353-5

Evans, J. S. B. T. (2003). In two minds: Dual process accounts of reasoning. *Trends in Cognitive Sciences*, *7*, 454–459. doi:10.1016/j.tics.2003.08.012

Evans, J. S. B. T. (2007). On the resolution of conflict in dual process theories of reasoning. *Thinking & Reasoning*, *13*, 321–339. doi:10.1080/13546780601008825

Fink, A., Grabner, R. H., Benedek, M., & Neubauer, A. C. (2006). Divergent thinking training is related to frontal electroencephalogram alpha synchronization. *European Journal of Neuroscience*, *23*, 2241–2246. doi:10.1111/ejn.2006.23.issue-8

Fink, A., Grabner, R. H., Benedek, M., Reishofer, G., Hauswirth, V., & Fally, M., et al. (2009a). The creative brain: Investigation of brain activity during creative problem solving by means of EEG and fMRI. *Human Brain Mapping*, *30*, 734–748. doi:10.1002/hbm.20538

Fink, A., Graif, B., & Neubauer, A. C. (2009b). Brain correlates underlying creative thinking: EEG alpha activity in professional vs. novice dancers. *Neuroimage*, *46*, 854–862. doi:10.1016/j.neuroimage.2009.02.036

Fink, A., & Neubauer, A. C. (2006). EEG alpha oscillations during the performance of verbal creativity tasks: Differential effects of sex and verbal intelligence. *International Journal of Psychophysiology*, *62*, 46–53. doi:10.1016/j.ijpsycho.2006.01.001

Fink, A., Schwab, D., & Papousek, I. (2011). Sensitivity of EEG upper alpha activity to cognitive and affective creativity interventions.

International Journal of Psychophysiology, *82*, 233–239. doi:10.1016/j.ijpsycho.2011.09.003

Foster, D. S. (1990). *EEG and subjective correlates of alpha frequency binaural beats stimulation combined with alpha biofeedback*. Memphis, TN: Memphis State University.

Gibson, C., Folley, B. S., & Park, S. (2009). Enhanced divergent thinking and creativity in musicians: A behavioral and near-infrared spectroscopy study. *Brain and Cognition*, *69*, 162–169. doi:10.1016/j.bandc.2008.07.009

Goel, V., & Vartanian, O. (2005). Dissociating the roles of right ventral lateral and dorsal lateral prefrontal cortex in generation and maintenance of hypotheses in set-shift problems. *Cerebral Cortex*, *15*, 1170–1177. doi:10.1093/cercor/bhh217

Grabner, R. H., Fink, A., & Neubauer, A. C. (2007). Brain correlates of self-rated originality of ideas: Evidence from event-related power and phase locking changes in the EEG. *Behavioral Neuroscience*, *121*, 224–230. doi:10.1037/0735-7044.121.1.224

Gruzelier, J. H., Holmesb, P., Hirstb, L., Bulpinc, K., Rahmanc, S., van Rund, C., & Leach, J. (2014). Replication of elite music performance enhancement following alpha/theta neurofeedback and application to novice performance and improvisation with SMR benefits. *Biological Psychology*, *95*, 96–107. doi:10.1016/j.biopsycho.2013.11.001

Jauk, E., Benedek, M., & Neubauer, A. C. (2012). Tackling creativity at its roots: Evidence for different patterns of EEG alpha activity related to convergent and divergent modes of task processing. *International Journal of Psychophysiology*, *84*, 219–225. doi:10.1016/j.ijpsycho.2012.02.012

Jaušovec, N. (1997). Differences in EEG activity during the solution of closed and open problems. *Creativity Research Journal*, *10*, 317–324. doi:10.1207/s15326934crj1004_3

Jaušovec, N. (2000). Differences in cognitive processes between gifted, intelligent, creative, and average individuals while solving complex problems: An EEG study. *Intelligence*, *28*, 213–237. doi:10.1016/S0160-2896(00)00037-4

Jen, C. H., Chen, H. C., Lien, H. C., & Cho, S. L. (2004). The development of the Chinese remote association test. *Research in Applied Psychology [in Chinese]*, *21*, 195–217.

Jones, T., Caulfield, L., Wilkinson, D., & Weller, L. (2011). The relationship between nonclinical schizotypy and handedness on divergent and convergent creative problem-solving tasks. *Creativity Research Journal*, *23*, 222–228. doi:10.1080/10400419.2011.595964

Jung, R. E., Segall, J. M., Bockholt, H. J., Flores, F. R., Chavez, R. C., & Haier, R. J. (2009). Neuroanatomy of creativity. *Human Brain Mapping*, *31*, 398–408.

Jung, T.-P., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., & Sejnowski, T. J. (2001). Analysis and visualization of single-trial event-related potentials. *Human Brain Mapping*, *14*, 166–185. doi:10.1002/(ISSN)1097-0193

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition-timing hypothesis. *Brain Research Reviews*, *53*, 63–88. doi:10.1016/j.brainresrev.2006.06.003

Kris, E. (1952). *Psychoanalytic exploration in art*. New York, NY: International Universities Press.

Lee, T.-W., Girolami, M., & Sejnowski, T. J. (1999). Independent component analysis using an extended infomax algorithm for mixed subgaussian and supergaussian sources. *Neural Computation*, *11*, 417–441. doi:10.1162/089976699300016719

Lin, W.-L., Hsu, K.-Y., Chen, H.-C., & Wang, J.-W. (2012). The relations of gender and personality traits on different creativities: A dual-process theory account. *Psychology of Aesthetics Creativity, and the Arts*, *6*, 112–123. doi:10.1037/a0026241

Lin, W.-L., & Lien, Y.-W. (2013). The different role of working memory in open-ended versus closed-ended creative problem solving: A dual-process theory account. *Creativity Research Journal*, *25*, 85–96. doi:10.1080/10400419.2013.752249

Lin, W.-L., Tsai, P.-H., Lin, H.-Y., & Chen, H.-C. (2014). How does emotion influence different creative performances? The mediating role of cognitive flexibility. *Cognition and Emotion*, *28*, 834–844. doi:10.1080/02699931.2013.854195

Lindsley, D. B. (1960). Attention, consciousness, sleep and wakefulness. In J. Field, H. W. Magoun, & V. E. Hall (Eds.), *Handbook of Physiology: Section 1. Neurophysiology* (Vol. 3, pp. 1553–1593). Washington, DC: American Physiological Society.

Makeig, S. (1993). Auditory event-related dynamics of the EEG spectrum and effects of exposure to tones. *Electroencephalography and Clinical Neurophysiology*, *86*, 283–293. doi:10.1016/0013-4694(93)90110-H

Martindale, C. (1999). Biological bases of creativity. In R. J. Sternberg (Ed), *Handbook of creativity* (pp. 137–152). Cambridge, MA: Cambridge University Press.

Martindale, C., & Armstrong, J. (1974). The relationship of creativity to cortical activation and its operant control. *Journal of Genetic Psychology*, *124*, 311–320. doi:10.1080/00221325.1974.10532293

Martindale, C., & Hasenfus, N. (1978). EEG differences as a function of creativity, stage of the creative process, and effort to be original. *Biological Psychology*, *6*, 157–167. doi:10.1016/0301-0511(78)90018-2

Mednick, S. A. (1962). The associative basis of the creative process. *Psychological Review*, *69*, 220–232. doi:10.1037/h0048850

Mednick, S. A., & Mednick, M. T. (1967). *Examiner's manual: Remote associates test*. Boston, MA: Houghton Mifflin.

Mölle, M., Marshall, L., Lutzenberger, W., Pietrowsky, R., Fehm, H. L., & Born, J. (1996). Enhanced dynamic complexity in the human EEG during creative thinking. *Neuroscience Letters*, *208*, 61–64. doi:10.1016/0304-3940(96)12539-8

Mölle, M., Marshall, L., Wolf, B., Fehm, H. L., & Born, J. (1999). EEG complexity and performance measures of creative thinking. *Psychophysiology*, *36*, 95–104. doi:10.1017/S0048577299961619

Norlander, T., & Gustafson, R. (1998). Effects of alcohol on a divergent figural fluency test during the illumination phase of the creative process. *Creativity Research Journal*, *11*, 265–274. doi:10.1207/s15326934crj1103_5

Noy, P. (1969). A revision of the psychoanalytic theory of the primary process. *International Journal of Psychoanalysis*, *50*, 155–178.

Pfenninger, K. H., & Shubik, V. R. (2001). Insights into the foundation of creativity: A synthesis. In K. H. Pfenninger, & V. R. Shubik (Eds.), *The origins of creativity* (pp. 213–236). Oxford, UK: Oxford University Press.

Pfurtscheller, G., Stancák, A., Jr., & Neuper, C. (1996). Event-related synchronization (ERS) in the alpha band—An electrophysiological correlate of cortical idling: A review. *International Journal of Psychophysiology*, *24*, 39–46. doi:10.1016/S0167-8760(96)00066-9

ProComp Infiniti System [Apparatus and software] (2003). Montreal, Canada: Thought Technology Ltd.

Raymond, J., Sajid, I., Parkinson, L., & Gruzelier, J. H. (2005). Biofeedback and dance performance: A preliminary investigation. *Applied Psychophysiology and Biofeedback*, *30*, 65–73. doi:10.1007/s10484-005-2175-x

Razumnikova, O. M. (2007). Creativity related cortex activity in the remote associates task. *Brain Research Bulletin*, *73*, 96–102. doi:10.1016/j.brainresbull.2007.02.008

Razumnikova, O. M., Volf, N. V., & Tarasova, I. V. (2009). Strategy and results: Sex differences in electrographic correlates of verbal and figural creativity. *Human Physiology*, *35*, 285–294. doi:10.1134/S0362119709030049

Schnitzler, A., & Gross, J. (2005). Normal and pathological oscillatory communication in the brain. *Nature Reviews Neuroscience*, *6*, 285–296. doi:10.1038/nrn1650

Simonton, D. K. (2008). Creativity and genius. In O. P. John, R. W. Robins, & L. A. Pervin (Eds.), *Handbook of personality: Theory and research* (pp. 679–700). New York, NY: Guilford Press.

Sloman, S. A. (1996). The empirical case for two systems of reasoning. *Psychological Bulletin*, *119*, 3–22. doi:10.1037/0033-2909.119.1.3

Stanovich, K. E., & West, R. F. (2000). Individual differences in reasoning: Implications for the rationality debate? *Behavioral and Brain Sciences*, *23*, 645–665. doi:10.1017/S0140525X00003435

Stent, G. S. (2001). Meaning in art and science. In K. H. Pfenninger, & V. R. Shubik (Eds.), *The origins of creativity* (pp. 31–42). Oxford, UK: Oxford University Press.

Suler, J. R. (1980). Primary process thinking and creativity. *Psychological Bulletin*, *88*, 144–165. doi:10.1037/0033-2909.88.1.144

Svensson, N., Archer, T., & Norlander, T. (2006). A Swedish version of the regressive imagery dictionary: Effects of alcohol and emotional enhancement on primary–secondary process relations. *Creativity Research Journal*, *18*, 459–470. doi:10.1207/s15326934crj1804_5

Torrance, E. P. (1974). *Torrance tests of creative thinking*. Lexington, MA: Personnel Press.

Varela, F., Lachaux, J.-P., Rodriguez, E., & Martinerie, J. (2001). The brainweb: Phase synchronization and large-scale integration. *Nature Reviews Neuroscience*, *2*, 229–239. doi:10.1038/35067550

Vernon, D., Egner, T., Cooper, N., Compton, T., Neilands, C., Sheri, A., & Gruzelier, J. (2003). The effect of training distinct neurofeedback protocols on aspects of cognitive performance. *International Journal of Psychophysiology*, *47*, 75–85. doi:10.1016/S0167-8760(02)00091-0

von Stein, A., & Sarnthein, J. (2000). Different frequencies for different scales of cortical integration: From local gamma to long range alpha/theta synchronization. *International Journal of Psychophysiology*, *38*, 301–313. doi:10.1016/S0167-8760(00)00172-0

Wakefield, J. F. (1989). Creativity and cognition some implications for arts education. *Creativity Research Journal*, *2*, 51–63. doi:10.1080/10400418909534300

Weisberg, R. W. (1995). Case studies of creative thinking: Reproduction versus restructuring in the real world. In S. M. Smith, T. B. Ward, & R. A. Finke (Eds.), *The creative cognition approach* (pp. 53–72). Cambridge, MA: MIT Press.

Wu, C. C. (1998). *The Chinese version of creative thinking test*. Taipei, Taiwan: Foundation for Scholarly Exchange.