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Enhanced divergent thinking and creativity in musicians: A behavioral and near-infrared spectroscopy study

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ABSTRACT

Empirical studies of creativity have focused on the importance of divergent thinking, which supports generating novel solutions to loosely defined problems. The present study examined creativity and frontal cortical activity in an externally-validated group of creative individuals (trained musicians) and demographically matched control participants, using behavioral tasks and near-infrared spectroscopy (NIRS). Experiment 1 examined convergent and divergent thinking with respect to intelligence and personality. Experiment 2 investigated frontal oxygenated and deoxygenated hemoglobin concentration changes during divergent thinking with NIRS. Results of Experiment 1 indicated enhanced creativity in musicians who also showed increased verbal ability and schizotypal personality but their enhanced divergent thinking remained robust after co-varying out these two factors. In Experiment 2, NIRS showed greater bilateral frontal activity in musicians during divergent thinking compared with nonmusicians. Overall, these results suggest that creative individuals are characterized by enhanced divergent thinking, which is supported by increased frontal cortical activity.

1. Introduction

While there are many distinct theories of creativity, it is generally agreed that the ability to draw on past experiences or ideas and combine them in novel ways lies at the heart of the creative process and that there are tremendous individual differences and variability in creativity (see Torrance, 1988; Folley & Park, 2005). Exceptionally creative people show a superior ability to conceptualize novel products and combine ideas in original ways, however, to some extent we all share this capacity to be creative (Raven, 2002) and the recognition of creative output depends on social processes as well as the individual ability or potential (Amabile, 1983).

Individual differences in creativity are modulated by certain cognitive skills and personality traits such as fluency, flexibility, visualization, imagination, expressiveness, openness to experience and increased schizotypal traits (Folley, 2006). A fundamental cognitive component of creativity that has been extensively studied since 1950s is the concept of "divergent thinking" which involves generating novel associations (Guilford, 1959; Mednick, 1962). Divergent thinking is distinguished from convergent thinking, which is defined by a narrowing of possible responses to reach the correct solutions. In contrast, divergent thinking involves flexible ideation to generate many responses to open-ended and multifaceted problems. Convergent thinking works best with well-defined problems that have a clearly defined response, while divergent thinking is best suited for poorly defined or unstructured problems. According to Guilford, it is divergent thinking that provides the foundation for creative production because it requires ideational searching without directional boundaries, and is determined by fluency, flexibility, and originality. Since Guilford's seminal contribution to the study of creativity, divergent thinking has remained as a conceptually, internally, and externally valid element of the creative process (Bartlett & Davis, 1974; Bennet, 1973; Cropley, 1972; Drevdahl, 1956; Harrington, Block, & Block, 1983; Hocevar, 1980; McRae & Costa, 1987; Milgram & Milgram, 1976; Runco, 1984; Runco, 1986; Runco, 1992; Torrance, 1988; Wallbrown & Huelsman, 1975; Zegas, 1976).

The creative thinking process has been associated with increased prefrontal (Folley & Park, 2005; Geake & Hansen, 2005; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005) and temporal cortical activity (Jung-Beeman et al., 2004). Bilateral activation of the frontal cortex and the anterior cingulate cortex was observed in a functional MRI study of solving letter string analogies, which involves convergent thinking (Geake & Hansen, 2005). A NIRS study of divergent thinking (Folley & Park, 2005) found bilateral increase in frontal activity when participants were engaged in generating novel uses for common objects (divergent

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thinking) but they also noted that individuals with elevated schizotypal personality tended to show greater right frontal activation. Increased creativity was most pronounced in these schizotypal subjects, thus providing an empirical link between creativity with psychosis-proneness. During a task that taps divergent thinking, the right prefrontal cortex showed significant activation when participants were asked to create stories in response to the presentation of unrelated words (Howard-Jones et al., 2005). In a simultaneous fMRI/EEG study that investigated remote (indirect) semantic associations, a bilateral increase in the right temporal activity was observed during creative insight solution development (Jung-Beeman et al., 2004), which involves both convergent and divergent thinking.

At this point, it is unclear whether creative thinking process engages bilateral or unilateral cortical regions, partly due to a wide range of creativity tasks used in imaging studies, some involving mostly convergent problem solving and others tapping more divergent thinking process. However, there is a broad consensus that the frontal cortex plays an important role. (Bekhtereva, Dan'ko, Starchenko, Pakhomov, & Medvedev, 2001; Bekhtereva et al., 2000; Carlsson, Wendt, & Risberg, 2000; Starchenko, Vorob'ev, Klycharev, Bekhtereva, & Medvedev, 2000).

Although the neural correlates of divergent thinking are beginning to be understood, most studies use laboratory measures of creativity and it is unclear how these measures are related to observable behaviors in the real world. Performing artists are implicitly assumed to have greater creative potential than the general population but it is unknown how personality variables, environment, and training interact to increase creativity in these individuals. Musicians are a particularly relevant population to study because of their intensive, long-term training that may have a significant impact on neural circuits that are associated with creativity.

Musical training at an early age can lead to altered brain structural development (Gaser & Schlaug, 2003). Using voxel-based morphometry (VBM), Gaser and Schlaug (2003) found gray matter volume differences among professional musicians (pianists), amateur musicians and nonmusicians in motor, auditory, and visual-spatial regions. More specifically, musician status was correlated positively with the volumes of the left precentral gyrus, left Heschl's gyrus, and right superior parietal cortex. Although this particular study did not find white matter differences, other studies reported evidence for larger corpus callosum (Lee, Chen, & Schlaug, 2002) and more efficient white matter organization (Schmithorst & Wilke, 2002) in individuals with extensive musical training. Therefore, it seems that music training may increase gray matter volumes in both hemispheres and there is some evidence to suggest that the connectivity of the two hemispheres may also be altered in musicians.

Behaviorally, musicians show anomalous cerebral dominance compared with nonmusicians; a shift towards sinistrality may be attributed to hand skill training (Hassler, 1990; Jäncke, Schlaug, & Steinmetz,1997) and necessary use of the nondominant hand during training since most musical instruments require the performers to work with both hands (Christman, 1993; Hassler & Gupta, 1993). These findings suggest that trained musicians may perform better than nonmusicians on cognitive tasks that require the two cerebral hemispheres, efficient inter-hemispheric communication and integration of dispersed neural networks because of the nature of their lengthy training.

The neural correlates of creativity in musicians were examined in two recent studies of pianists. In an fMRI study, Bengtsson and colleagues (2007) observed increased activation of the right dorsolateral prefrontal cortex, the presupplementary motor area, the rostral portion of the dorsal premotor cortex, and the left posterior superior temporal gyrus during improvisation in classical pianists. The importance of frontal cortex in relation to creativity was also highlighted in a new fMRI study of professional jazz pianists while they engaged in improvisation (Limb & Braun, 2008). Spontaneous improvisation was accompanied by a pattern of activation and deactivation in the frontal cortex. A decreased activation of dorsolateral prefrontal and lateral orbital regions was observed along with increased activation of the medial prefrontal (frontal polar) cortex in jazz musicians. Although the neural networks implicated in these two studies differ, they both implicate the role of frontal cortical regions in creative improvisation.

There is evidence to indicate brain structural differences and the involvement of frontal cortical regions during creative musical improvisation in trained musicians. Therefore it was logical to ask if trained musicians might show increased creativity in nonmusical tasks as well. The present study examined creative thinking in musicians and nonmusicians, using behavioral and near infrared spectroscopy (NIRS) experiments. NIRS is a noninvasive neuroimaging method that allows in-vivo measurement of changes in the concentrations of oxygenated hemoglobin (oxyHb) and deoxygenated hemoglobin (deoxyHb) in the cortex based on their distinctive optical properties (Jobsis, 1977). We hypothesized that musicians would show enhanced divergent thinking accompanied by increased bilateral prefrontal cortical activity.

2. Experiment 1: Behavioral Investigation of creativity in musicians and nonmusicians

2.1. Materials and methods

Participants: Twenty classical music students (9 women) were recruited from Vanderbilt University's Blair School of Music. Inclusion criteria for the musician group were as follows: current playing of an instrument and musical training for more than 8 years. Instruments played included the piano, woodwind, string, and percussion instruments. The mean duration of musical training was 11.10 years ($SD = 3.65$) and mean hours of practice per day was 2.50 ($SD = 1.41$). 20 nonmusicians (11 women) were recruited from an introductory psychology course at Vanderbilt University. Nonmusicians had no music training beyond the regular curricular exposure to music during the kindergarten to high school years. The two groups were matched in age, education and sex (see Table 1). In addition, the admissions criteria for the Blair School of Music and those for the College of Arts and Sciences were not different in terms of the standardized test scores (i.e. the Scholastic Aptitude Test) and high school grades. The admissions statistics are available on the Vanderbilt University website (www.vanderbilt.edu). Exclusion criteria for both groups were DSM-IV (Diagnostic and Statistical Manual for Psychiatric Disorders IV; American Psychiatric Association, 1994) diagnosis for psychiatric disorder, psychotropic medication, history of head injury or neurological disorders, and illegal drug use. All participants gave written informed consent approved by the Vanderbilt University Institutional Review Board and they were paid.

2.1.2. Design and procedure

Participants were asked to complete questionnaires and participate in two behavioral experiments in one session.

Intelligence was assessed by the Wechsler Abbreviated Scale of Intelligence (WASI, The Psychological Corporation, 1999). Handedness was assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). Verbal fluency was measured by the "FAS" task (Spreen & Strauss, 1998) which requires participants to generate words that begin with the letters F, A and S with one minute response time limit per letter.

Table 1
Demographic information

	Participants in Experiment 1		Participants in Experiment 2	
	Musician ($N = 20$)	Nonmusician ($N = 20$)	Musician ($N = 8$)	Nonmusician ($N = 7$)
Number of women	9	11	5	4
Age	19.5 (1.1)	18.6 (0.7)	19.7 (1.2)	19.1 (1.3)
Education	14.1 (0.9)	13.4 (0.7)	14.1 (0.8)	13.6 (0.9)
Edinburgh handedness	49.2 (55.1)	70.2 (35.8)	58.8 (51.0)	74.2 (16.9)
Verbal IQ	116.4 (8.9)	107.2 (9.9)	117.4 (9.2)	110.5 (12.5)
Performance IQ	111.7 (10.0)	107.5 (9.9)	113.6 (12.9)	115.7 (10.2)
Full scale IQ	115.9 (7.0)	108.3 (8.5)	117.5 (10.3)	114.7 (11.4)

Personality scales: The Gough Personality Scale (Gough, 1979) is a 30-item self-report measure of creativity on personality characteristics in which the participant is asked to select out of 30 adjectives (e.g. conventional, snobbish, sincere, etc.) those characteristics that apply to him/herself. The range of score is 0–18 with greater scores indicating increased creative personality traits.

The Schizotypal Personality Questionnaire (SPQ; Raine, 1991), a self-report measure, consisting of 74 true-false items was used to assess schizotypy, which is associated with psychosis-proneness in the general population. The reason for including SPQ was that in previous studies (e.g., Abraham, Windmann, Daum, & Güntürkün, 2005; Carson, Peterson, & Higgins, 2003; Folley & Park, 2005), schizotypal personality was associated with increased creativity. SPQ consists of three factors (Raine, 1991) that tap different aspects of psychosis–proneness: Cognitive–Perceptual, Interpersonal and Disorganized. Cognitive–Perceptual factor corresponds to subtle perceptual aberrations and magical thinking. The interpersonal factor is related to difficulties in forming social relationships and reduced social and emotional functioning. The disorganized factor is linked to odd behavior and odd speech.

Creativity tasks: We used the Remote Associates Test (Mednick, 1962) and a novel divergent thinking task developed by Folley and Park (2005) based on earlier models of creativity (Guilford, 1959; Torrance, 1988; Wallach & Kogan, 1965).

The Remote Associates Test (RAT) is a paper-and-pencil test of associative processing. In a RAT trial, participants are given a set of three stimulus words and are asked to find another word that is associated with all three words in the set. For example, given the stimulus set of 'blue', 'cake' and 'cottage,' the correct answer would be 'cheese'. The RAT requires participants to generate semantic associations for all three words in a set and search for the link that connects them. This process requires both divergent and convergent thinking in order to generate and link the remote associations. Participants were instructed to write down all the associations that they generated and their final solution word. There were thirty trials. Accuracy (% correct) and the total number of associations generated were recorded.

The Divergent Thinking Test (DTT) required subjects to generate 'uses' for real objects. Each trial began with the presentation of the stimulus objects. Participants were asked to explore the objects and generate uses for them alone and in combination with one another. Responses were recorded verbatim. There was no time limit. When participants indicated that they finished generating 'uses,' the next trial began with the presentation of a new set of familiar objects. The stimulus objects were selected based on the results from a previous study by Folley and Park (2005). Each trial contained multiple objects and number of objects ranged from 3 to 5. Thus the task demand was varied with increasing the "combinatory load" (i.e., generating uses for a combination of the objects). There were three trials.

2.2. Results

Group differences were tested with ANOVAs. Correlations were computed to examine associations among creativity, personality and intelligence measures.

Demographic and neuropsychological variables (see Table 1): Musicians and nonmusicians did not differ in handedness ($F(1,39) = 1.89$, $p = .19$). Musicians scored higher on the verbal ($F(1,39) = 9.44$, $p = .004$) and full scale IQ ($F(1,39) = 7.88$, $p = .008$) scales than did the nonmusicians. On the verbal fluency task, musicians ($M = 49.5$, $SD = 10.8$) produced a greater number of words than did nonmusicians ($M = 41.4$, $SD = 10.7$) ($F(1,39) = 2.44$, $p = .02$).

Gough personality scale: Musicians ($M = 12.3$, $SD = 0.80$) scored higher on the Gough scale than did nonmusicians ($M = 10.1$, $SD = 0.57$) ($F(1,39) = 5.00$, $p = 0.031$) suggesting that the musicians were more creative on this self-report measure.

Schizotypy: Musicians scored higher on the SPQ overall ($M = 27.9$, $SD = 10.5$) compared to nonmusicians ($M = 20.6$, $SD = 10.3$), $F(1,39) = 4.90$, $p = .03$). For the Cognitive–Perceptual factor, there was a main effect for group ($F(1,39) = 4.1$, $p = .049$); musicians ($M = 11.2$, $SD = 6.1$) scored higher than nonmusicians ($M = 7.9$, $SD = 4.2$). For the Disorganization factor, there was a main effect of group ($F(1,39) = 16.01$, $p < .001$); musicians ($M = 9.10$, $SD = 3.2$) scored higher than nonmusicians ($M = 4.95$, $SD = 3.4$). There were no significant differences between musicians and nonmusicians in the Interpersonal factor, ($F(1,39) = .01$, $p = .91$).

Remote associates test (RAT): Musicians gave more correct responses ($M = 25.2$, $SD = 12.8$) than nonmusicians ($M = 15.9$, $SD = 10.4$), ($F(1,39) = 6.32$, $p = 0.02$) but they did not differ in the number of associations generated ($F(1,39) = .01$, $p = .92$). To address the influence of enhanced verbal functioning in musicians, we examined RAT performance after co-varying for verbal IQ and fluency. The group difference in RAT accuracy was no longer significant after verbal fluency ($F(1,39) = .35$, $p = .56$) and verbal IQ, ($F(1,39) = .59$, $p = .45$) were co-varied out. Therefore, better RAT performance in musicians may stem from their enhanced verbal ability.

Divergent thinking test (DTT): For single objects, musicians ($M = 36.2$, $SD = 21.9$) generated a greater number of "uses" than did nonmusicians ($M = 22.3$, $SD = 12.1$), ($F(1,39) = 6.19$, $p = .02$). Similarly, for combinatory uses, musicians ($M = 12.7$, $SD = 7.3$) generated more "uses" than did nonmusicians ($M = 7.8$, $SD = 4.05$), ($F(1,39) = 6.94$, $p = .012$). After co-varying for verbal ability, the group difference in the total number of uses remained significant ($F(1,39) = 4.74$, $p = .04$); the corrected number of uses generated was 46.2 ($SD = 4.1$) for musicians and 32.7 ($SD = 4.1$) for nonmusicians. Thus increased divergent thinking in musicians remained robust even after their superior verbal abilities were taken into account.

Correlations: For all participants, verbal functioning had a significant impact on RAT performance; accuracy was correlated with verbal IQ ($r = 0.41$, $p = .009$). The Gough score correlated significantly with the percentage correct on the RAT ($r = 0.483$, $p = 0.0014$) but not with the number of associations generated ($r = -0.02$, $p = 0.89$). The Gough also correlated with the number of single object uses on the DTT ($r = 0.482$, $p = 0.0014$) but not with the combinatory uses score on the DTT ($r = 0.20$, $p = 0.23$). Total SPQ score was not associated with the RAT accuracy ($r = 0.19$, $p = 0.25$) or with the RAT number of associations ($r = -0.15$ $p = .36$). However, the SPQ Disorganized factor was correlated with RAT accuracy ($r = 0.37$, $p = 0.02$). There were no significant correlations among SPQ scores and the DTT.

2.3. Discussion

These results suggest that musicians have increased convergent and divergent thinking compared with nonmusicians. Musicians also showed increased trait creativity as indexed by the Gough scale, which suggests that musicians do indeed show enhanced creative personality. Musicians also scored higher than nonmusicians on the Schizotypal Personality Scale (SPQ). The SPQ scores did not have an additional impact on their increased convergent and divergent thinking in musicians in contrast to the results from a previous study in which the SPQ scores were associated with increased divergent thinking (Folley & Park, 2005). However, it must be noted that in the Folley and Park's study, the schizotypal individuals's mean SPQ score was greater than 20 above that of the control subjects. In the present study, the musicians scored higher than the nonmusicians but their scores were well within the normal, nonclinical range.

The musicians in our study had higher full scale IQs and verbal IQs than nonmusicians. We recruited both groups from the same selective university and they were matched demographically based on age, years of education and gender. Yet the music students had higher IQ scores than did nonmusicans. This result is in agreement with recent studies that found that extensive music training is associated with increased full scale IQ (Schellenberg, 2004) and enhanced verbal ability (Chan, Ho, & Cheung, 1998; Moreno & Besson, 2006; Schellenberg, 2004; Schön, Magne, & Besson, 2004).

Although the superior verbal ability in musicians was a major factor in enhanced RAT performance, which requires both convergent and divergent thinking, better DTT performance of musicians could not be explained by their increased verbal fluency or IQ. There are some key differences in the RAT and the DTT. First, the RAT is a verbal task whereas DTT is a multimodal task with a verbal output. In the DTT, participants first looked at the stimuli but they also used other sensory modalities, especially tactile and sometimes auditory. Thus it is possible that the DTT recruits a wider, more bilateral neural network in addition to the language-related, more left-lateralized circuits. Second, the RAT has a correct solution but the DTT is open-ended. This difference in the goals of the two tasks may also be a key difference that contributes to how the subjects approached these two tasks and the IQ tests consist problems that have correct solutions.

Why are musicians better at divergent thinking than nonmusicians? One possibility is that some aspects of music training may enhance cognitive and neural mechanisms that are recruited for divergent thinking. After all, musicians engage in improvisation and many create music in addition to playing instruments. In addition, the brain organization of musicians may be especially conducive to creative thinking. Extensive music training involves reorganization of cortical structures and function (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Pantev et al., 1998; Schlaug, Jäncke, Huang, Staiger, & Steinmetz, 1995) including reduced hemispheric asymmetry and efficient interhemispheric interactions (Patston, Kirk, Rolfe, Corballis, & Tippett, 2007; Schlaug, Jäncke, Huang, & Steinmetz, 1995), which are in turn, associated with creative thinking (Geake & Hansen, 2005; Folley & Park, 2005). It is possible that music training influences brain organization such that the resulting cognitive system is prone to divergent thinking. To elucidate the cortical functioning during DTT in musicians, we used near infrared spectroscopy (NIRS) to study frontal cortical activation.

3. Experiment 2: A near-infrared spectroscopy study of prefrontal function during divergent thinking

We examined frontal activation during creative thinking with a modified divergent thinking task using near infrared spectroscopy (NIRS) in a randomly selected subset of participants from Experiment 1. NIRS is a noninvasive neuroimaging method that allows in vivo, photometrical measurement of changes in the concentrations of the oxyhemoglobin (oxyHb) and deoxyhemoglobin (deoxyHb) in the cortex (Jobsis, 1977). NIRS is sensitive enough to measure the physiological blood oxygenation changes in the cortex during cognitive tasks in healthy subjects (Hoshi & Tamura 1993; Fallgatter & Strik 1998).

3.1. Materials and methods

Participants: Eight musicians (5 women) and seven nonmusicians (4 women) were recruited at random from the participants who took part in Experiment 1. Inclusion and exclusion criteria were identical to those described in Experiment 1. The mean duration of musical training was 10.5 years ($SD = 2.1$) and mean hours of practice per day was 1.7 ($SD = 0.7$) for the musicians. The two groups were matched in age, education and sex (see Table 1). In addition, all the behavioral data collected in Experiment 1 were available for group comparisons.

3.1.1. Design and procedure

NIRS during modified DTT: NIRS was performed using 22 channels of a 780–830 nm spectrometer (ETG-100 system; Hitachi Medical Corp), composed of emitter–detector pairs. Each emitter was composed of two continuous laser diodes (3 mW ± 0.15 mW on 'high' power) with different wavelengths (780 ± 20 and 830 ± 20 nm) that were amplitude modulated (0.6 and 1.5 kHz). Near-infrared signals were mixed and transmitted through an optical fiber cable placed on the scalp using a spring-loaded probe. Another optical fiber carried the scattered signal picked up by the optical sensor to a photodiode. An inter-fiber spacing of approximately 27 mm produced a light penetration close to 20 mm. Probes were placed on the forehead according to the International 10–20 system of EEG electrode placement (Fig. 1) with RH probes covering areas Fp2, F4 and F8, and LH probes covering areas Fp1, F5 and F7.Signals were acquired at a sample rate of 10 Hz from 22 cortical regions on the bilateral frontal cortex using the 3×5 probe holder and the corresponding optodes. The signal was amplified, demodulated, and then digitized. The detected signals were converted to chromophore concentrations using the modified Beer–Lambert Law (Obrig et al., 2000) to obtain changes in oxyhemoglobin (oxyHb), deoxyhemoglobin (deoxyHb) and total hemoglobin (total Hb). Changes in chromophore concentrations are observed with a 0.1-s temporal resolution and 20–30 mm spatial resolution. Utilization of different wavelengths of light enables separation of chromophore contributions to the hemodynamic response, and decreases in deoxyHb accompanied by increases in oxyHb and total Hb provide a representation of physiologic cortical activation (Zaramella et al., 2001). Thus, all chromophores are reported.

A modified DTT using pictures of common household objects was used in a block design for the NIRS experiment (Fig. 2). Modifying the behavioral task from Experiment 1 was necessary to avoid motion artifact produced during speaking. Therefore, the

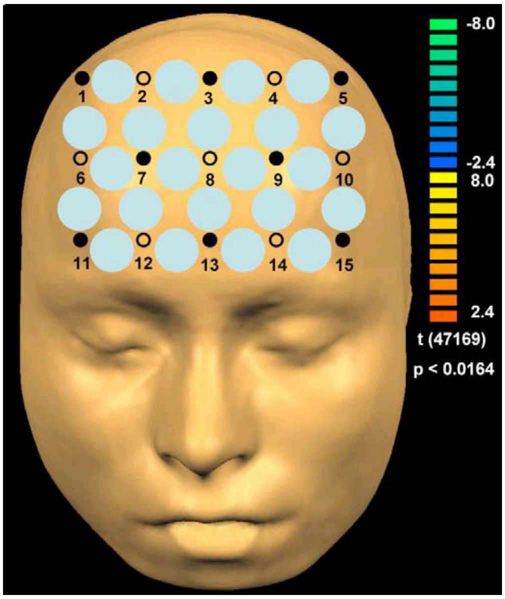

Fig. 1. Placement of the 3 × 5 probe holder on the frontal lobe. Odd numbered circles represent emitters and even numbered circles represent detectors. Large circles show measurement channels.

modified DTT required key presses during NIRS recording, but we recorded the ideas generated immediately after each run (see below).

In the modified DTT, a target object was presented above a central fixation point on a computer screen with an array of 8 other, numbered objects below the fixation point. Subjects were required to decide which objects in the array could be 'used' with the target. They indicated their response by pressing number keys corresponding to the numbered objects. To control for the perceptual, categorization, decision-making and motor response components of the DTT, we included a control task. We needed to ensure that the cortical activation observed was not due to pressing keys or examining an array of visual stimuli and having to group them. In the control task, a target stimulus object was presented above the central fixation point on the computer screen with an array of eight other numbered objects below it. Participants were required to decide which objects were similar in color to the target and indicate their choices by pressing the keys corresponding to the numbered objects. Identical items were shown during the control and DT tasks. The key presses were recorded.

Each run contained 1 color control and 1 DT tasks and was conducted as follows: there was a 15-s baseline fixation at the beginning of each run. Next, an instruction screen was presented for 5 s that alerted subjects to prepare for the "color" task. Then, a stimulus screen containing objects was presented for 30 s during which subjects made their responses. There was a 15-s fixation period followed by a 5-s instruction screen that alerted subjects to prepare for the "uses" task. Then the stimulus screen was presented for 45 s during which subjects made their responses by pressing the appropriate key. This was followed by another 15 s fixation period. This sequence of events constituted one run. Immediately after each run, the DT stimulus screen was displayed again indefinitely and subjects were asked to verbalize their responses that they had made in the previous run. This was done to verify the ideas generated during the modified DTT. The verbal responses were recorded by the experimenter. There were 6 runs per subject.

Data processing: Matlab™ was used to process raw absorbance data. Data were downsampled from 10 to 1 Hz, then normalized and converted to chromophore measurements using the modified Beer–Lambert Law. Linear drift correction and statistical measurements were performed using *Brain Voyager QX™*. Contrasts were protected from alpha inflation by the false discovery statistic q(FDR). Within-subjects (DT vs. control task) and between-subjects contrasts were performed. Using the general linear model, statistical parametric maps were generated using the BrainVoyager QX with the group (musicians and nonmusicians) and task (DT and color tasks) as regressors.

3.2. Results

Demographic and neuropsychological variables (see Table 1): Musicians and nonmusicians did not differ in handedness ($F(1,14) = .71$, $p = .49$), verbal IQ ($F(1,14) = 1.41$, $p = .26$), performance IQ ($F(1,14) = .10$, $p = .76$), full scale IQ ($F(1,14) = .24$, $p = .64$) and verbal fluency ($F(1,14) = .93$, $p = .35$).

Behavioral measures of creativity from Experiment 1: The DTT, RAT and Gough scale scores from Experiment 1 were used to compare musicians and nonmusicians in this study. For DT for single objects, there was a trend towards musicians ($M = 43.2$, $SD = 27.1$) generating a greater number of "uses" than did nonmu-

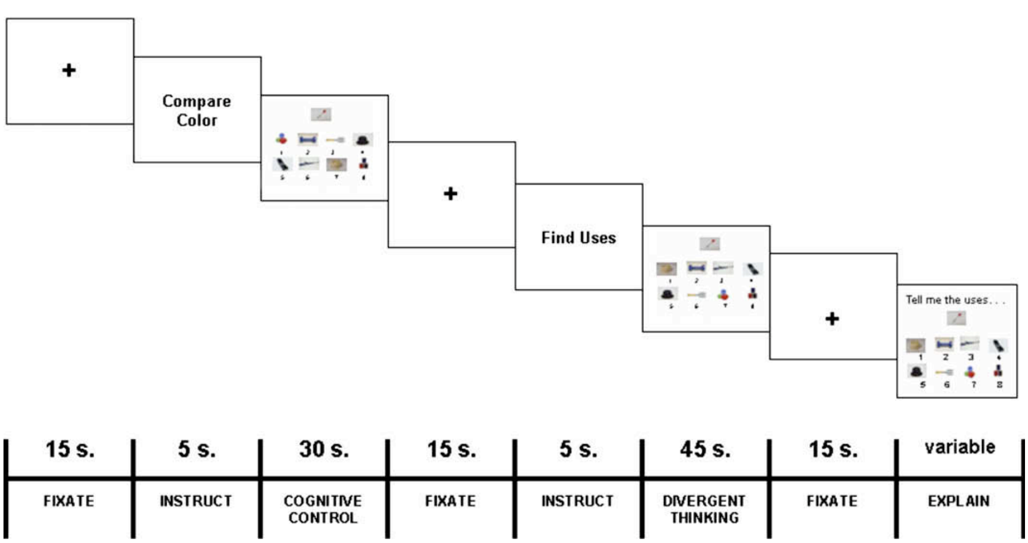

Fig. 2. A schematic diagram of the modified divergent thinking task (DTT) and the control task performed during NIRS.

sicians ($M = 21.2$, $SD = 10.8$), ($F(1,14) = 3.50$, $p = .08$). For combinatory uses on the DTT, musicians ($M = 11.6$, $SD = 5.6$) generated more "uses" than did nonmusicians ($M = 6.3$, $SD = 1.97$), ($F(1,14) = 4.77$, $p = .048$). On the RAT, although musicians ($M = 28.5$, $SD = 15.5$) scored numerically higher than nonmusicians ($M = 15.0$, $SD = 13.5$), this difference did not reach statistical significance ($F(1,14) = 3.03$, $p = .11$). On the Gough scale, musicians ($M = 12.2$, $SD = 3.1$) scored higher than nonmusicians ($M = 8.7$, $SD = 2.8$) ($F(1,14) = 4.19$, $p = .05$).

Schizotypy: Musicians and nonmusicians did not differ in the total SPQ scores ($F(1,14) = .25$, $p = .63$). There was no main effect of group ($F(1,14) = .43$, $p = .52$) in the Disorganization factor and in the Interpersonal factor ($F(1,14) = .047$, $p = .51$). But there was a trend towards difference in the Cognitive–Perceptual factor ($F(1,14) = 4.25$, $p = .06$); musicians ($M = 12.2$, $SD = 5.0$) scored higher than nonmusicians ($M = 6.8$, $SD = 4.6$).

Modified DTT and NIRS: The number of uses generated in the modified DT condition and the number of similar colors in the color control task as recorded by the key press were compared with ANOVA. Behaviorally, there was no main effect of the group in the color task ($F(1,14) = 2.21$, $p = .17$) with the musicians ($M = 22.4$, $SD = 6.8$) and nonmusicians ($M = 27.0$, $SD = 9.1$) performing similarly. In other words, the two groups selected about the same number of items as belonging to the same color category. There was also no difference between musicians ($M = 17.6$, $SD = 2.4$) and nonmusicians ($M = 19.4$, $SD = 3.5$) on the modified DTT ($F(1,14) = 3.08$, $p = .11$). This means they selected about the same number items to be used together and indicated their choices by key presses.

We examined the changes in oxyhemoglobin (oxyHb), deoxyhemoglobin (deoxyHb) and total hemoglobin (totalHb) concentrations in the frontal cortex for DTT compared with the color control task in musicians and nonmusicians. We compared the musicians with nonmusicians by subtracting the hemoglobin levels of the nonmusicians from those of the musicians. Group comparisons indicated a greater bilateral prefrontal increase in oxyHb and totalHb for musicians compared with nonmusicians during the DTT compared with the Color control task (see Fig. 3). The deoxyHb data did not indicate a clear pattern.

3.3. Discussion

Greater bilateral frontal activity was observed in musicians during the modified DTT compared with the control task even when the performance during NIRS was matched across the two groups. For all three chromophores, there was a similar pattern, although to a different degree depending on the chromophore. Musicians had a clear bilateral increase in oxyHb and totalHb compared to nonmusicians in the frontal cortex. Nonmusicians seemed to show greater concentrations of all 3 chromophores in the left than right frontal cortex (although more for deoxyHb and totalHb compared to oxyHb). Thus, musicians recruit more bilateral frontal network during DT whereas nonmusicians may rely more on the left hemisphere. Thus there is evidence for bilateral processing in musicians compared to nonmusicians; nonmusicians may rely on a more left-lateralized, verbally mediated strategy that might hinder divergent thinking in this experimental context.

Although the modified DTT used for the NIRS did not differentiate the two groups behaviorally, these musicians had higher DT for combinatory uses and Gough scores than nonmusicians outside the scanner. The full version of the DTT used in Experiment 1 differed from the modified version used in NIRS in two significant ways. For the NIRS, the DTT was modified to have a time limit for the responses and instead of verbal responses, key presses were used. This modification possibly reduced the sensitivity of the task. However, their brain activation pattern still differed and the behavioral measures of creativity obtained from Experiment 1 were still enhanced in this small subset of musicians who participated in NIRS.

The SPQ scores did not differentiate musicians from nonmusicians in Experiment 2 but the sample size was very small. Nevertheless, there was a trend towards group difference in the Cognitive–Perceptual subscale, with musicians scoring higher than nonmusicians.

There are some limitations to consider. First, the sample size was small, however the participants were well characterized and demographically matched. Second, NIRS measures were obtained from the frontal cortex only, which somewhat limits the interpretation. Creative thinking involves a complex neural network in addition to the frontal regions but owing to the limited number of channels available in the NIRS equipment, we had to select a cortical region a priori. Studies of whole-brain activation patterns during divergent thinking should be conducted in the future to examine the role of temporal cortex in divergent thinking. Third, convergent thinking is also a key component of creativity but we did not address it in the NIRS study. Jung-Beeman and colleagues (2004) have examined the neural correlates of convergent thinking and they point to the role of right temporal cortex. Future studies could address both divergent and convergent thinking in the same subjects to further our understanding of the relationship between these two aspects of creativity.

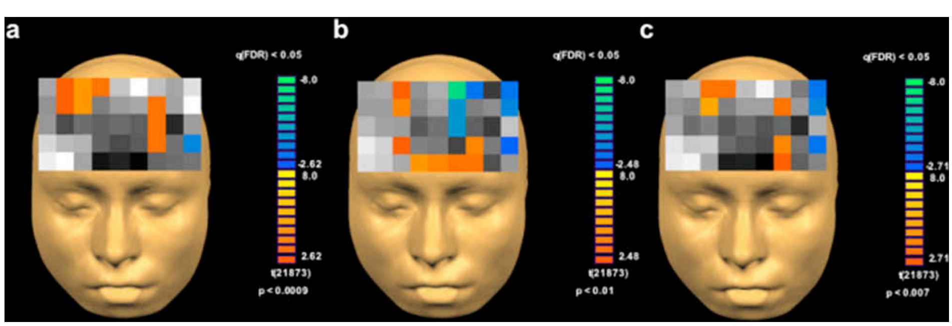

Fig. 3. NIRS activation maps comparing musicians and nonmusicians. Chromophore concentrations during the control task were subtracted from those during the divergent thinking task for each group to derive activation maps for the three chromophores. Then group difference maps were generated by subtracting the nonmusians from the musicians. (a) OxyHb levels: Increased bilateral frontal cortical oxyHb levels in musicians compared with nonmusicians (see red areas). (b) DeoxyHb levels: Musicians and nonmusicians show different patterns of deoxyHb concentrations levels during DT. Nonmusicians appear to show increased deoxyHb levels in the left frontal cortex (indicated by blue–green areas) whereas musicians show more bilateral increase in deoxyHb levels (see red–orange areas). (c) TotalHb levels: Bilateral increase in totalHb levels in musicians compared with nonmusicians in the frontal cortex (see red areas). Nonmusicians show more activation in the left frontal cortex (see blue areas). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

Even with these potential limitations, the difference between musicians and nonmusicians in the recruitment of frontal cortex during divergent thinking appears to be robust.

4. General discussion

The behavioral data from Experiment 1 supported our hypothesis of enhanced creative thinking in musicians. These results motivated an investigation of the neural correlates of creativity in Experiment 2 with NIRS. We observed greater bilateral frontal activation during a divergent thinking task than during a control task in the musicians.

An important finding in the current study was the increased IQ scores of the musicians, which is interesting in itself. There have been studies that point to the benefits of music training that include increased verbal functioning (e.g. Chan, Ho & Cheung,1998). Our data are in agreement with the past results. Since the musicians showed superior verbal ability, a question arose as to whether increased creativity could be simply due to greater intelligence. We examined this issue by co-varying for verbal IQ and fluency. Indeed, better verbal ability contributed to enhanced RAT, which requires both divergent and convergent thinking but not to the DTT performance. We posit that verbal intelligence contributes more significantly to convergent thinking, which, as Guilford (1959) states, require the identification of a single solution to a well-defined problem. The significant group difference in DTT even after co-varying for verbal IQ and fluency, suggests that generating novel ideas requires something more than verbal abilities.

While increased sinistrality or mixed handedness is often found in musicians (Jäncke, Schlaug, & Steinmetz, 1997; Hassler, 1990), we did not find increased left-handedness in musicians in our study. So the bilateral frontal activation pattern observed cannot be attributed to increased mixed handedness or sinistrality in our study. On the other hand, it could be argued that music training may enhance recruitment of both hemispheres. Playing a musical instrument requires bimanual dexterity. Musicians recruited in our study played various instruments that require both integrated and independent bimanual activity (e.g. 11 piano, 3 woodwind, 11 strings, 1 percussion) with 9/20 of them playing two or more instruments. Christman (1993) distinguishes between temporally integrated bimanual activity (in which both hands must be coordinated to play an instrument) required in playing strings and woodwinds, and more independent bimanual activity (in which the hands move independently) required to play the piano. The former group was found to exhibit weaker degrees of handedness and greater bilateral hemispheric integration. However, all musical instruments require the performer to centrally integrate the activities of the two hands over time. For example, playing the piano requires both independent and coordinated movements of the hands. The left and the right hand execute different sequences of movements but the timing of the movements of the two hands must be centrally coordinated in time. In sum, across a wide range of musical instruments, it is likely that a high level of interhemispheric coordination and cooperation must be achieved by the performer.

Previous studies had observed an association of schizotypy and creativity (Leonhard & Brugger, 1998; Gianotti, Mohr, Pizzagalli, Lehmann, & Brugger, 2001; Folley & Park, 2005; Abraham et al., 2005; Weinstein & Graves, 2001; Carson et al., 2003). In the present study, while schizotypy was significantly increased in the musicians, it was not correlated with creativity measures. Perhaps this is because both groups were within a nonclinical, normal range of SPQ scores; the mean SPQ score of the musicians was 27.9 compared with 20.6 for the nonmusicians. In the study by Folley and Park (2005) the mean SPQ score of the schizotypal undergraduate students was 44.7 and that for the control students was 20.9.

Another way to interpret the results of the present study is to note the fact that there are many routes to increased divergent thinking and creativity. Highly schizotypal and psychosis-prone individuals may show increased divergent thinking because they have the neurocognitive profile that is conducive to remote and indirect associations. Musicians may show enhanced divergent and convergent thinking due to their extensive training and experience that facilitates performance on these tasks. Thus, increased schizotypy may be one of several factors contributing to increased creativity.

To summarize, we found evidence for increased creativity in trained musicians from behavioral and functional neuroimaging results. Enhanced divergent thinking may indicate a potential for efficient, flexible thinking and the ability to generate novel solutions, which may be supported by increased recruitment of the frontal cortex.

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