学位論文の要約

保健科学分野博士課程

Neural correlates of musical improvisation performance: a magnetoencephalographic investigation (即興演奏に伴う神経活動：脳磁計による探究)

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Introduction:

Improvisation is the art or act of doing anything spontaneously without previous preparation. All of us engage in it in some form or another, in varying degrees, throughout our daily lives. Every social interaction we have is arguably a form of improvisation. Responding swiftly to the sudden occurrence of problems or stressor could also be said to require improvisation. Correspondingly, our willingness to voluntarily put ourselves in new or unpredictable situations could also be said to be contingent upon our willingness and ability to improvise. Seen in this light, improvisation is thus an extremely important and useful life skill to train and develop.

Musical improvisation offers one way of training improvisation that is easily implementable regardless of space or mental, physical or technical ability. Essentially a form of non-verbal communication training, musical improvisation training is well known to enhance skills important for social interaction in healthy populations. Perhaps because of this, musical improvisation is used in clinical therapies for those who struggle with social, communication, executive, motor, or cognitive dysfunction. In clinical populations as well, musical improvisation has been reported to improve social function. Furthermore, in both healthy and clinical populations, experience training musical improvisation is associated with enhanced creativity.

Despite these positive training-based outcomes on sociability and creativity, widespread adoption and acceptance of musical improvisation as a viable therapeutic, training and educational tool has been hampered by a lack of neurophysiological support. However, this problem is poised to be solved, as rapid advancements in neuroimaging technology over the beginning of this century have given rise to a growing field interested in the brain activity underlying musical improvisation. From functional magnetic resonance imaging (fMRI), positron emission topography (PET), electroencephalography (EEG), and transcranial magnetic stimulation (TMS), numerous modalities have begun to elucidate the nature of brain activity during musical improvisation. The emerging picture in experienced musical improvisers is that musical improvisation is characterized by increased spontaneous, internal, and integrative processing. In facilitation of this processing, experienced improvisers are also thought to engage in disinhibition during improvisation, a cognitive state that is characterized by decreased activity in areas functionally associated with inhibitory control. However, how brain activity in different oscillatory frequency bands is modulated in different brain areas due to improvisational music performance has hitherto been largely unclarified. To this end, studies employing magnetoencephalography (MEG), which permits spectral-spatial analyses of brain activity, are well suited. Some MEG studies regarding music performance have been reported. However, aside from my own work, I have found no reports regarding improvisational music performance in MEG.

The primary goal of this thesis was to demonstrate the feasibility of musical improvisation performance experimentation in MEG, and produce results that would not only have practical relevance, but also drive future studies regarding musical improvisation training/therapy and contribute neurophysiological evidence supportive of their wider implementation. To accomplish this, I designed MEG compatible music instruments, and an MEG musical improvisation performance paradigm akin to conversational improvisation styles used in live music and therapy. Using these instruments and paradigm, I conducted MEG studies to spectral-spatially differentiated brain activity important for musical improvisation performance in both non-musicians (Study 1) and musicians (Study 2A). Additionally in musicians, I furthermore explored the relationship between creativity and the brain activity associated with disinhibition during musical improvisation performance (Study 2B).

Methods:

Study 1 targeted 13 right-handed students from the present institution (8 males and 5 females; mean ± SD age, 21.8 ± 0.9). None had any musical improvisation experience. Study 2A targeted 13 right-handed musicians (10 males and 3 females; mean ± SD age, 35.7 ± 8.6 years) with an improvisational playing frequency ranging from several days a week to several hours per day. Study 2B targeted 14 right-handed musicians, 13 of whom were from Study 2A, and an additional female subject with only marginal improvisation experience (10 males and 4 females; mean ± SD age, 35.7 ± 8.9 years). Written informed consent was obtained from all subjects prior to participation.

The instruments used for music performance were made from Piezo sensors, fixed in place to prevent magnetic interference of MEG measurement. In Study 1, the instrument comprised a single Piezo sensor programmed to produce a tom drum sound. Drum performances were monotonic using the index finger of the right hand. In Study 2, the instrument was a five-key keyboard programed to produce a piano sound over a C major pentatonic scale. Keyboard performances were polytonic using all five fingers of the right hand. Performances on the instruments were based on two response conditions: Copy, where subjects mimiced the rhythm of the stimulus; and Improvise, where subjects played a novel response to the stimulus.

The MEG musical improvisation performance experimental paradigm was conducted as a randomized block design. Each block comprised a series of stimulus-response epochs which further comprised four musical bars. Essentially, in the first bar, stimulus pattern based on sounds from the performance instrument was presented. In the second bar, subjects then performed a response to the stimulus via mental imagery in accordance with the appropriate condition (i.e. Improvise or Copy) of that block. Then in the third bar, subjects physically performed their imagined response on the corresponding MEG instrument. Finally in the fourth bar, the subjects rested. Baseline brain activity was based on this rest period. The resulting performances thus resembled a conversational "call and response" design that is often used in live music and therapy.

Based on the MEG signals recorded for Improvise and Copy, the source of the spontaneous activity was estimated (minimum norm estimation). Source activity was parcellated into 68 cortical areas based on the Desikan Kilany anatomical map, and further decomposed into three frequency bands: theta (5-7 Hz), alpha (8-12 Hz), beta (15-29 Hz); and normalized as a percent deviation from baseline. For Study 2A and 2B, behavior was assessed based on the number of notes played during physical performance (hereafter: note count). In Study 2B creativity was assessed using the S-A creativity test. Subjects received a total creativity score from 1-10. Those scoring above the mean were placed in a high creativity (HC) group. Those scoring below the mean were placed in a low creativity (LC) group. Study 2B, which was focused on disinhibition, analyzed brain activity specifically in right prefrontal areas known for inhibition control:

precentral gyrus (PrCG), rostral middle frontal (RMF), pars opercularis (POP), pars orbitalis (POB), and the pars triangularis (PTR). Study 2B furthermore used differential values of brain activity between conditions, calculated by taking activity during Copy and subtracting it from that during Improvise, resulting in an I-C value.

All analyses of brain activity focused on that recorded during mental imagery separately in the theta, alpha, and beta frequency bands. For Study 1 and 2A, differences between Improvise and Copy brain activity in each frequency band were explored via RM ANOVA. For Study 2A, differences in performance note count between conditions were additionally analyzed using paired t tests. Moreover, the relationship between note count and brain activity was analyzed via multiple regression. Finally, Study 2B analyzed the differences between inhibition associated I-C brain activity in each frequency band and creativity group, and differences in note count between groups using mixed ANOVA.

Results:

In Study 1, no differences between Improvise and Copy conditions were found in the theta activity. In the alpha band, broad non-specific differences were found in the left hemisphere, and specifically in the right superior parietal cortex. In the beta band, specific differences between conditions were found in the left precuneus cortex (PCu) and the left caudal anterior cingulate (CAC).

In Study 2, differences between conditions in theta activity were found isolated in the left temporal cortex, specifically in the: fusiform gyrus (FFG) ($p = 0.047$), inferior temporal gyrus (ITG) ($p = 0.023$), middle temporal gyrus (MTG) ($p = 0.009$), superior temporal gyrus (STG) (p

= 0.030), and parahippocampal gyrus (PHG) ($p = 0.049$). Left-hemispheric differences in the alpha band were also found predominantly in the parietal cortex, and included: precentral gyrus (PCG) ($p = 0.019$), superior parietal cortex (SPC) ($p = 0.017$), inferior parietal cortex (IPC) ($p = 0.017$), supramarginal gyrus (SMG) ($p = 0.045$), precuneus (PCu) ($p = 0.021$), and posterior cingulate cortex (PCC) ($p = 0.040$). Differences in beta activity between conditions were also found, interestingly in right prefrontal areas known for inhibition control: RMF ($p = 0.040$), and the PCG ($p = 0.045$). Behaviorally, there were also significant differences between conditions, with subjects note counts for Improvise (mean ± SE, 8.841 ± 0.302) significantly higher than those for Copy (mean ± SE, 6.880 ± 0.145) ($p < 0.001$), and significantly greater than the mean note count for all 16 stimulus patterns ($p < 0.001$), reflecting expression of increased rhythmical freedom when improvising. Multiple regression analyses revealed that note count was predictive of brain activity in the alpha frequency band in the left IPC ($F(2, 23) = 4.207$, $p = 0.028$, R2 = 0.268) and the left PCC ($F(2, 23) = 3.439$, $p = 0.049$, R 2 = 0.230). Standardized beta coefficients for the contribution of note count in these two areas were respectively $\beta = -0.593$ ($p = 0.044$) and $\beta = -0.663$ ($p = 0.029$), indicating a trend towards decreased alpha band brain activity with higher note count. However, the 61 standardized beta coefficients for the contribution of condition in these two areas were respectively $\beta = 0.806$ ($p = 0.008$) and $\beta = 0.730$ ($p = 0.017$), indicating the greater importance of condition over note count at predicting alpha activity, and corroborating the RM ANOVA finding that alpha activity levels are higher for Improvise than for Copy.

As for Study 2B, the mean creativity score was 6.88. Thus those that scored 7 or above were placed in the HC group (N=8, 6 males and 2 females, average age ± SD: 35.3 ± 9.3 years), and those that scored 6 or below were placed in the LC group (N=6, 4 males and 2 females, average

age ± SD: 36.3 ± 7.5). Mixed ANOVA of I-C theta activity revealed that I-C values were significantly lower for the HC group compared to the LC group in the pars opercularis (POP) (mean ± SE; -4.640 ± 1.873 vs. 5.760 ± 2.163; p = 0.003), RMF (mean ± SE; -5.227 ± 1.521 vs. 1.554 ± 1.757; p = 0.013), and PrCG (mean ± SE; -1.008 ± 1.993 vs. 7.777 ± 2.301; p = 0.014). Intriguingly, the pattern of I-C theta activity in each of these three brain areas was opposite between groups, with negative mean values for the HC group, and positive mean values for the LC group. This means that theta activity for Improvise was lower than Copy in the HC group, and vice versa in the LC group. No differences in I-C activity between groups were found in the alpha or beta bands. However, mean beta activity in the RMF and PrCG did reveal a tendency towards the same inverse pattern between the HC and LC groups seen in the theta band: -1.418 ± 4.50 vs. 0.690 ± 3.525, and -1.267 ± 3.421 vs. 0.550 ± 3.567, respectively. Behaviorally, note counts for the HC group (mean ± SE, 9.219 ± 0.401) were significantly higher than the LC group (mean ± SE, 7.865 ± 0.463) (p = 0.047). Looking at groups separately, there was no significant difference in note count between Improvise (mean ± SE, 7.865 ± 0.463) and Copy (mean ± SE, 6.865 ± 0.217) in the LC group, whereas note count was significantly higher for Improvise (mean ± SE, 9.219 ± 0.401) than Copy (mean ± SE, 6.844 ± 0.188) in the HC group ($p < 0.001$). Multiple regression analyses revealed that note count during Improvise, and creativity group, together were significantly predictive of I-C brain activity in the theta frequency band in the right POP (F(2, 11) = 6.079, p = 0.017, R2 = 0.525), the right RMF (F(2, 11) = 4.004, p = 0.049, R 2 = 0.421), and the right PrCG (F(2, 11) = 4.799, p = 0.032, R2 = 0.466). However, standardized beta coefficients for the contribution of note count during Improvise were not significant in any of these areas at β = 0.036 (p = 0.886), β = -0.094 (p = 0.737), and -0.281 (p = 0.305). Instead, the contribution towards I-C theta activity appeared to be based on creativity group, whose beta coefficients for POP, RMF, and PrCG were respectively, $\beta = -0.743$ ($p = 0.012$), $\beta = -0.594$ ($p = 0.052$), and $\beta = -0.489$ ($p = 0.088$).

Discussion:

As for Study 1, areas with significant differences between conditions overlap those known for their role in sensorimotor integration and action planning. For both alpha and beta activity, levels for Improvise were lower than for Copy. Decreased alpha activity is often interpreted as a sign of external, goal-directed focus. Indeed, alpha activity for both Copy and Improvise decreased compared to baseline. However, that brain activity during the novel and free response generation of Improvise was more goal-directed than Copy, where subjects had to memorize and mimic the stimulus in their response, was illogical. Another interpretation considers the fact that decreased alpha activity can also be a sign of inefficient neural function. Thus less alpha activity for Improvise and Copy was interpreted to reflect less coordinated sensorimotor integration processing during improvisation for these non-musicians. Meanwhile, decreased beta activity in the CAC is linked to motor planning and increased higher-order processing, and emotional activity. Therefore, although gamma activity was not verified in this thesis, the beta results could comprehensively be indicative of increased emotional processing, as well as increased higher-order processing for planning/decision making and sensorimotor integration in Improvise compared to Copy.

As for Study 2A in improvisationally experienced musicians, theta activity in the left temporal cortex is well associated with auditory processing and production, particularly in processing related to auditory communication, including that related to semantics and emotion. Considering the well-known similarities between music and language, the higher theta activity found for Improvise may comprehensively reflect an increased demand on rhythmic communication processing. As for alpha differences, they occurred predominantly in sensorimotor integration areas. In line with arguments put forth for Study 1, increased alpha in these areas is associated not only with more internally-directed, but also more efficient processing. Thus, the greater alpha activity for Improvise than Copy was interpreted to reflect more internal, efficient, and coordinated sensorimotor processing during improvisation. Meanwhile, increased beta activity in inhibition control areas is associated with active inhibition. Thus, less beta activity for Improvise than Copy was interpreted to potentially reflect disinhibition during improvisation.

Finally, regarding the results of Study 2B, there was less theta activity for Improvise than Copy in the HC group, and vice versa for the LC group in inhibition control areas. Theta activity is linked to the regulation of higher-order processing. Although not significant, beta activity exhibited group trends similar to theta activity in these same areas. The results could thus indicate that these inhibition control areas were more fundamentally disengaged with less higher-order processing occurring in those with higher creativity, a strong sign of disinhibition. Intriguingly, this was a phenomenon that was not seen in those with lower creativity. This implies that disinhibition is not a given for musicians during musical improvisation, even for those who have improvisational experience. Rather, disinhibition during improvisation appeared to depend upon creative ability. Multiple regression results corroborate this (see Figure 21), revealing that disinhibitory theta band activity (i.e. negative I-C theta activity) is only predicted by creativity group and not by Improvise note count. This finding could furthermore indicate that the beta band results in Study 2A were biased by the larger number of musicians with high creativity scores. Overall, the results of Study 2B indicate a relationship between creative ability and control of inhibitory function, and highlight the importance of assessing inhibition-associated brain activity and creative ability in future studies examining the effects of musical improvisation training.

Conclusions:

In Study 1, the inexperience of the non-musicians was reflected by inefficient sensorimotor integration processing. Improvisationally experienced musicians in Study 2A meanwhile exhibited brain activity that highlighted the communicative nature of the improvisational style used, and support the notion that production of novel auditory content may be facilitated by more efficient integrative processing, and a disinhibited cognitive state. Finally, the results of Study 2B highlighted the importance of disinhibition as a cognitive strategy during improvisation for improvisationally experienced musicians with higher creative ability.

Overall, far more than merely demonstrating the feasibility of musical improvisation performance experimentation in MEG, the present thesis has produced results that corroborate findings from other modalities, and deepen the knowledge in this field. Most importantly, the establishment of its practical conversational musical improvisation performance paradigm provides a solid foundation for further direct neuromagnetic investigation into the effects of improvisational music training and therapy that will hopefully support its wider implementation.

The work in this thesis resulted in the following publication based on Study 2A:

Boasen, J., Takeshita, Y., Kuriki, S., & Yokosawa, K. (2018). Spectral-spatial differentiation of brain activity during mental imagery of improvisational music performance using MEG. *Frontiers in Human Neuroscience*, 12. https://doi.org/10.3389/fnhum.2018.00156