hypersonic effect followed the presentation of a hypersonic shower and the fundamental brains of the subjects were activated.

3.2.3. Results of the psychological experiment

The subjective assessment of 4 of 13 questionnaire items revealed that the hypersonic shower condition caused less discomfort and garnered higher positive ratings than the control condition with statistical significance. The items that showed statistical significance ($p < 0.05$) were "the sound inside the train was not noisy", "the sound inside the train was unexpectedly pleasant", "I did not get tired of the sound" and "I was not annoyed" (Figure 8).

As observed above, we confirmed that merely adding HFCs, to the acoustic environment, rather than playing a hypersonic announcement, in a railway car would induce the hypersonic effect although the degree of the effect was smaller than that of the full-hypersonic condition in which a hypersonic announcement and hypersonic shower are presented. The results support the validity of the hypersonic shower as a viable way to create an acoustic environment more comfortable.

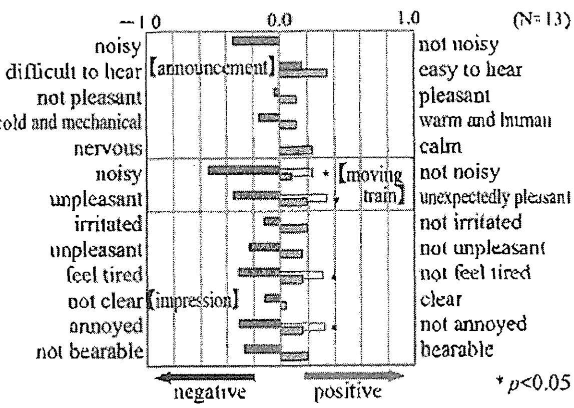

Figure 8: Mean score of each item in the questionnaire in Experiment 2.

3.3. Experiment 3: Investigation of the duration of the hypersonic sound presentation

3.3.1. Overview

The sound presentation in the above experiments was 12 minutes per trial while we are often in actual railway cars for a longer period of time. Therefore, in Experiment 3 we presented an acoustic environment with HFCs for a longer duration, 21 minutes. We investigated the temporal influence using alpha 2 EEG potential as an index. The EEGs of the subjects were continuously recorded while the sound was presented to them in the control condition, first for 21 minutes, followed by either the control sound again or a hypersonic shower sound for the same duration. Nine subjects with normal hearing ability (five males and four females, ranging in age from 38 to 62) participated in the experiment.

3.3.2. Results of physiological experiment

For all seven temporal intervals (three minutes each), alpha 2 EEG potentials in the hypersonic shower condition were higher than those in the control condition (Figure 9a). A statistical test of the full 21 minutes showed the value $p = 0.061$ which was close to a significance level of $p = 0.05$ even though the number of subjects was below ten (Figure 9b). Moreover, we traced the transition of alpha 2 EEG potential every three minutes and observed that the potential in the hypersonic shower condition showed a more significant increase ($p<0.05$) at the temporal interval between 15 and 18 minutes and a more highly significant increase ($p < 0.001$), at the temporal interval between 18 and 21 minutes, from the beginning of the presentation than that in the control condition. The magnitude of increase of those potentials grew over time. On the contrary, when the control condition sound was presented twice in a row, there was no appreciable difference between the first and second presentations.

These results show the possibility that hypersonic effect becomes stronger over time. It is expected that a long-term presentation of hypersonic sound in a railway car would cause no negative effect and that the longer presentation is, the greater the positive effect would be.

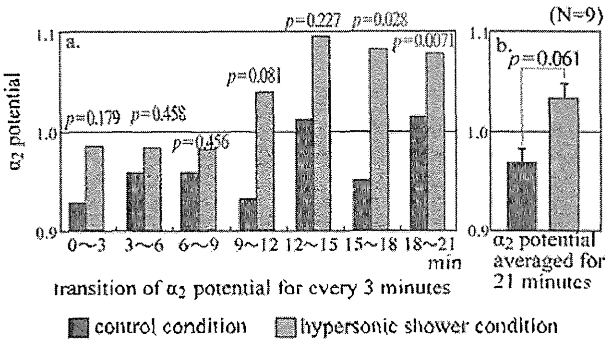

Figure 9: Mean alpha 2 EEG potentials in seven temporal intervals (three minutes each), (a) and that with SD over all 21 minutes (b) in Experiment 3.

3.4. Experiment 4: Examination of the effect of the order of sound presentation

3.4.1. Overview

Taking into account that the emergence of the hypersonic effect observed in the fundamental brain is delayed by tens of seconds after the onset of the hypersonic sound, and remains until about 100 second after its termination, we designed experimental procedures to present sounds without HFCs first, then those with HFCs for the present study. Thus, the results shown above are not sufficient on their own to clear the suspicion of the effect order might play when two kinds of sound materials are presented consecutively. To examine the possibility of the second condition always increasing the activity of the fundamental brain, we presented the control condition with a duration of 21 minutes twice consecutively and recorded the EEG of the subjects to analyse the alpha 2 potential extracted from the recorded data at 3-minute intervals. The experiment was performed in an experimental space the same size as that in railway car simulator. Nine subjects with normal hearing ability (three males and six females, ranging in age from 38 to 62) participated in the experiment.

3.4.2. Results of physiological experiment

None of the seven 3-minute intervals showed significant differences in the alpha 2 potential between the first and second sound presentations (Figure 10). These results indicate that the hypothesis that the second condition always would increase the activity of the fundamental brain when two kinds of sound materials are presented consecutively was refuted and the reliability of the results of the present study showing the activation of the fundamental brain by the hypersonic shower is confirmed.

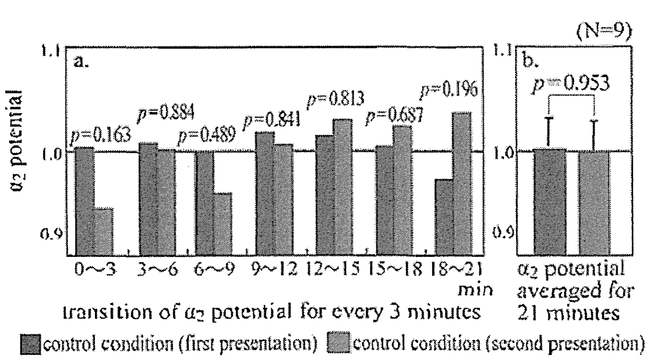

Figure 10: Mean alpha 2 EEG potentials in seven temporal intervals (three minutes each), (a) and that with SD over all 21 minutes (b) in Experiment 4.

3.5. Experiment 5: Hypersonic effect on earphone-wearers

3.5.1 Overview

The number of passengers using earphones on the train has increased rapidly in recent years. On the other hand, it has been suggested that humans have an unknown information channel for HFCs inducing the hypersonic effect, which does not use air conduction for hearing, but exists on the surface of the body including the head [Oohashi et al. 2006; Yagi 2013]. By applying this finding, we examined passengers wearing earphones in a train to test if exposing their body surface to HFCs would have any effect on them.

In trains earphone users have been increased rapidly in recent years. On the other hand, it has been suggested that humans have an unknown information channel for high frequency components inducing hypersonic effect, which is not using air conduction hearing, but exists on body surface including the head [Oohashi et. al 2006, Yagi 2013]. By applying this finding, we examined earphone-using passengers in a train to prove if the exposure of high frequency components to their body surfaces is effective to them.

The subjects were instructed to bring a piece of music of their choice recorded on their own portable players. They were asked to play back and listen to the music, which was in effect high-cut digital sound, only through earphones. The same interval of music was repeated in each condition. The sound stimuli, therefore, were different for different individuals but consistent for each individual. All subjects wore common, securely fitting, inner-ear type earphones (ATH-CLP330, Audio-Technica, Tokyo, Japan).

Two conditions were presented: full-hypersonic and control. In the full-hypersonic condition, virtual car-interior environmental sounds, a hypersonic shower and a hypersonic announcement were presented to the body surface of the subjects, while high-cut sounds through earphones were presented to the air-conducted auditory system. In the control condition, the virtual car-interior environmental sounds and the high-cut announcement were presented to the body surface, while high-cut sounds were sent through earphones to the air-conducted auditory system. Fourteen subjects with normal hearing ability (eight males and six females, ranging in age from 34 to 62) participated in the physiological experiment, and sixteen subjects (nine males and seven females, ranging in age from 34 to 62) participated in the psychological experiment.

3.5.2. Results of the physiological experiment

The alpha 2 potential recorded from subjects who listened to music through earphones in a full-hypersonic condition was significantly higher than that of those who listened in the control condition (Figure 11, p=0.014). The p value was smaller than that observed in Experiments 2-3 in which subjects did not wear earphones (Figure 5, p=0.032), which means a higher significance. In other words, when the car-interior environmental sounds had a hypersonic shower presented at the same time, the hypersonic effect was observed in earphone-wearers showing remarkable activation of the fundamental brain with high statistical significance.

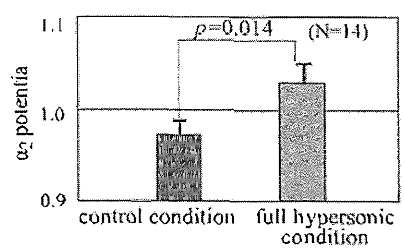

Figure 11: Mean and SD of the increase in alpha 2 potentials under two conditions in Experiment 5.

3.5.3. Results of the psychological experiment

Statistical significance was observed showing a tendency toward less unpleasant and good feeling in the full-hypersonic condition for 2 of the 15 items (Figure 12): "The sound inside the train was not noisy" and "unexpectedly pleasant". The items regarding the public announcement showed no significance, which can be explained by the fact that announcements cannot be heard well by those wearing earphones.

3.5.4. The applicability of the methodology

When managing a public acoustic environment by adding and presenting specific sounds, it is extremely difficult to induce a universally positive effect with statistical significance on a group of people because of the diversity in individual preference for sound and music. The methodology we employed, on the contrary, helped us to overcome individual differences. We removed audible components from rainforest sounds, extracted only the inaudible HFCs that do not produce individual preferences since the sounds are not recognized. We filled the entire public space with these inaudible components, while individuals listening to their favourite music through earphones. In this way, we succeeded in satisfying individual preferences and, at the same time, allowed the general public to have a more comfortable experience via the universal hypersonic effect.

We used an innovative methodology that integrated personal preference and universal physiological reaction productive of multiple effects, in which we presented individually chosen music to the subject's system through earphones, while presenting HFCs to the body surface through speakers.

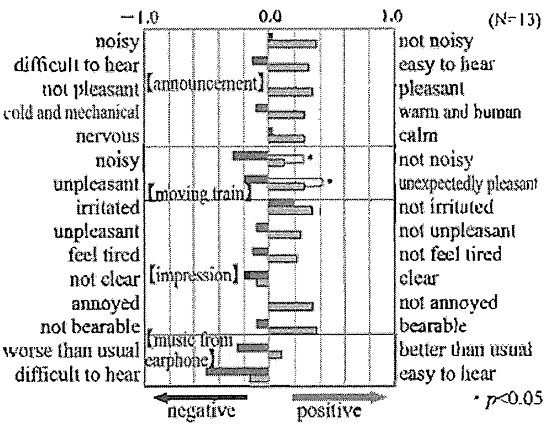

Figure 12: Mean score of each item in the questionnaire in Experiment 5

4. Discussion

We will first discuss the methodology by which we carried out the current research including the construction of experimental environments, then the significance of the results of physiological and psychological experiments that demonstrated the activation of the brain function obtained using the above methodology, and finally the features of our approach to this research.

First, to create a simulation system to use within a railway car simulator, we made accurate four-channel recordings of the acoustic environment inside an actual moving train filled with passengers, and developed a method by which to build a virtual acoustic environment with high actuality so that the subject would feel that the train was actually in motion. Along with this realistic sound space, we also build a reproduction system for high fidelity hypersonic sound. We also established a method by which to develop hypersonic content that would improve the car-interior acoustic environment. Our method added HFCs extracted from the environmental sounds of a rainforest to the sound of a public announcement that had only contained an audible frequency component.

Secondly, we employed the alpha 2 potential of the subjects' EEGs as a physiological measure. In a previous experiment in which we simultaneously measured regional cerebral blood flow and EEGs, alpha 2 potential proved to have a significantly high positive correlation with the total activity of the fundamental brain network originating in the midbrain and diencephalon. Therefore, the fact that alpha 2 potential increased more significantly when a hypersonic shower or a hypersonic announcement was added to the car-interior acoustic environment than in the control condition when only the usual car-interior acoustic environment was presented suggests that the hypersonic effect had actually been induced and the fundamental brain was activated [Nakamura et al., 2004] (Figure 13).

What is the significance of the activation of the fundamental brain function? First of all, the fundamental brain regions activated by hypersonic sound include the neural structures related to the wide-range regulation system originating from the midbrain, especially the reward-generating system [Oohashi et al., 2000]. The reward-generating system includes the dopaminergic, serotoninergic, and noradrenalinergic systems that produce a desire for beauty and comfort, and a pleasure sensation when beauty and comfort are realized. Increase in the activation of these neural systems makes us feel the sensory information from the surrounding environment to be more beautiful and pleasant. The results of the present psychological experiments suggest that by adding a hypersonic shower or hypersonic announcements to the car-interior acoustic environment, the activity of the reward-generating system increased and thus the impression of the acoustic environment drastically changed from a negative one to a positive one. In addition, it has been reported that the hypersonic effect improved the acuteness of the sensitivity [Nishina et al., 2010] and the cognitive function [Suzuki et al., 2013] through the activation of the fundamental brain network. Such improvements in brain function can be seen by the impression that the announcement was easy to hear in the present experiment. Our strategy to improve the acoustic environment by altering human sensitivity to sounds was validated through the present physiological and psychological measurements.

The hypothalamus, a part of the diencephalons which constitutes part of the fundamental brain, is the highest center of the autonomic nervous system consisting of the sympathetic and parasympathetic nerves. It is, at the same time, one of the essential bases of our immune system. It focuses attention on the physiological impairment induced by the disorder and decline in brain function in these regions related to many modern diseases. Therefore, the fact that fundamental brain function can be activated on public transportation by embedding hypersonic sound as reported in this paper suggests that media technology may have the potential for a novel contribution to overcoming various modern diseases caused by the disorder of fundamental brain functions. This is expected to become an application that might add new value to public transportation used by all kinds of people.

Third, we approached the problem of how to improve the unpleasant acoustic environment in a railway car in a way distinct from that of previous researchers who tried to exclude or reduce the source of the noise. We solved the

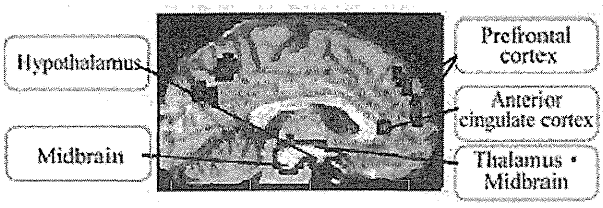

Figure13 Activated regions of fundamental brain by the hypersonic sound.

problem with a novel strategy. By presenting inaudible complex HFC sounds in the railway car, we induced the hypersonic effect and modulated the passengers' sensitivity to sounds, thus making them feel the acoustic environment to be more pleasant. This study has suggests that our approach is more advantageous than previous ones. Crucial in inducing this hypersonic effect was the HFCs extracted from natural tropical rainforest environmental sounds. Presentation of these HFCs in the railway car does not increase the noise level or disturb other sounds, such as public announcements, that are used to provide information to passengers. In addition, because HFCs are inaudible, they do not induce individual preferential responses, which may be induced by audible sounds. In this sense, the experiment that most typically represents the feature of this approach is the one delivering music of individual preference through earphones while presenting HFCs to body surface. In this experiment, we showed statistically significant improvement of the acoustic environment realized by activation of the fundamental brain while each passenger satisfied an individual sound preference. Such a methodology by which to improve the acoustic environment utilizing the effect of inaudible HFCs is unique in terms of harmoniously integrating individual psychological responses and universal physiological responses from the viewpoint of originality, effectiveness, novelty and generality.

The various results obtained in this study verify the availability and feasibility of the application of the hypersonic effect to improve a car-interior acoustic environment, while at the same time, these results indicate a possible breakthrough in the application of the hypersonic effect to other fields.

5. Conclusions

By applying cutting-edge media technology, we have added complex HFCs to a car-interior acoustic environment that is widely recognized to be poor and unpleasant. This induced the hypersonic effect and activated the fundamental brain network that generates pleasure and beauty, by means of which the impression of the car-interior acoustic environment was extremely improved. These results suggest that, by inducing hypersonic effect to passengers by adding complex HFCs to car-interior acoustic environments, we can improve the car-interior acoustic environments through the mechanism of inducing the more pleasant acceptance of the sound even if its audible components are identical. The results demonstrate the availability, feasibility and enormous possibility of the applications of the hypersonic effect as a novel technology to improve a car-interior acoustic environment. Future studies will include the development of a sound-presenting system and sound contents to apply the hypersonic effect in an actual train, and the application of this methodology to acoustic environments other than that in a railway car.

Acknowledgement

This work was partly supported by JSPS through the "Funding Program for Next Generation World-Leading Researchers," initiated by the Council for Science and Technology Policy for E.N., by the Grants-in-aid for Scientific Research [22135008] for M.H., and by the Japan Science and Technology Agency through the Core Research for Evolutional Science and Technology Program.

References

Kitagawa, Nagakura, K, 2012, Countermeasures for sound propagation in railway noise, *The Journal of the Accoustical Society of Japan*, 68-12,622-627.

Nakamura S, Honda M, Morimoto M, Yagi R, Nishina E, Kawai N, Maekawa T. Oohashi T. 2004. Electroencephalo- graphic evaluation of the hypersonic effect, *Society for Neuroscience Abstract*, 752.1.

Nishina, E, Oohashi, T, 2005. Study on the improvement of urban sound environment by the sound with in-audible high frequency components, *City planning review*, 40-3, 169-174.

Nishina, E, Oohashi, T, 2007. 'Physiological and psychological evaluation on the improvement of urban sound environment applying hypersonic effect, *City planning review*, 42-3, 139-144.

Nishina, E, et al, 2010, Hypersonic sound track for Blu-ray Disc "Akira", *ASIAGRAPH 2010 proceedings*, 53-58.

Oohashi, T et al, 1991. High-frequency sound above the audible range affects brain electric activity and sound perception, *Audio Engineering Society 91st Convention Preprint*, 3207.

Oohashi T, Nishina E, Honda M, Yonekura Y, Kawai N, Maekawa T, Shibasaki H et al., 2000. Inaudible high-frequency sounds affect brain activity, A hypersonic effect, *Journal of Neurophysiology*, 83, 3548-3558.

Oohashi, T, Kawai, N, Nishina E, Honda, M, Yonekura, Y, Shibasaki, H et al, 2006. The role of biological system other than auditory air-conduction in the emergence of the hypersonic effect, *Brain research*, 1073-1074, 339-347.

Oohashi, T, 2013, Introduction to hypersonic effect, *KAGAKU*, 83-3,296-301.

Onodera, E, Nishina, Yagi, R, Fukushima , A, Kawai, N, Oohashi, 2012. T. A preliminary study for the improvement of the sound environment in the public transport, *2012 Autumn Meeting, Acoustical Society of Japan*, 1067-1068.

Onodera, E, Nishina, E, Nakagawa T, Yagi, R, Fukushima , A, Kawai, N, Oohashi, T, 2013. A fundamental study for the improvement of the sound environment at the station platforms, *2013 Spring Meeting, Acoustical Society of Japan*, 1119-1120.

Suzuki,Y, 2013. Hypersonic effect and performance of recognition tests, *KAGAKU*, 83-3,343-345.

Yagi, R, Kawai, Nishina, Emi, Oohashi, T, 2003. Multi parametric Evaluation of the Effects of Intensity of Inaudible High Frequency Sounds in Hypersonic Effect, *Transactions of the Virtual Reality Society of Japan*, 213-220

Yamamoto, T, Takai, K, Hiramatsu K, 1990. *Souon no Kagaku* (Science of Noise), 38, Kaiseisya.

非西欧文化圏の芸術に含まれる超高密度視聴覚情報の生理的心理的効果
- アジア太平洋の芸術の真髄を高臨場感で再現するために-
Physiological and psychological effect of high density audio-visual information on traditional performance and art of non-Western culture
──Penetrating the essence of Asian-Pacific performance and art via media

仁科エミ/放送大学・総合研究大学院大学, 河合徳枝/国際科学振興財団・早稲田大学, 大橋　力/国際科学振興財団・文明科学研究所
NISHINA Emi[1]/The Open University of Japan,, SOKENDAI, KAWAI Norie[2]/Foundation for Advancement of International Science, Waseda University, OOHASHI Tsutomu[3]/Foundation for Advancement of International Science, Yamashiro Institue of Science and Culture
*[1]nishina@ouj.ac.jps, *[2]kawai@action-net.jp, *[3]oohashi@fais.or.jp

Abstract: We have discovered that some sound from musical instruments in non-Western traditional culture, such as Japanese *biwa*, *shakuhachi* and Balinese *gamelan* sound, contain rich high-frequency components above human audible range, which significantly activate the entire network of the fundamental brain. The brain regions activated by the sound with non-stationary inaudible high frequency components, include the neural structures related to the wide-range regulation system originating from the midbrain, especially the reward-generating system. Increase in the activation of reward-generating systems makes us feel the sensory information from the surrounding environment to be more beautiful and pleasant. The hypothalamus, which constitutes part of the fundamental brain, is the highest center of the autonomic nervous system consisting of the sympathetic and parasympathetic nerves, and is one of the essential bases of our immune system. It focuses attention on the physiological impairment induced by the disorder and decline in brain function in these regions related to many modern diseases. We also found a 4K image of high density paintings showing the activation of fundamental brain. Our results indicate that we should consider, in addition to its technological possibilities, the human reaction and the cultural diversity in response to the audio-visual format to penetrate the essence of Asian-Pacific performing art via media.

Keywords: hypersonic effect, high frequency components, 4K image, traditional music .

1. Introduction

Our research group has travelled to many places in the world, from around Asia to deepest Africa, in pursuit of musical performances and the appreciation of visual arts in their indigenous setting and surroundings over about 40 years. Our research leader Oohashi ascertained that the some instrumental and vocal sound from non-Western culture emitted from a compact disc (CD) was significantly inferior to the live sound that he had heard in the field. The difference in fidelity between the CD sound and the live sound of non-Western musical instruments even exceeded that achieved by modern Western European musical instrumental sounds produced, for example, by piano or orchestra. Oohashi, with his distinguished career of music composition and record production in professional studios, felt that this qualitative difference was comparable to that existing between the sound of CDs and LPs. A.k.a. artist Yamashiro Shoji, Oohashi is the leader of the *Geinoh Yamashirogumi,* the Japanese music group.

Studios producing commercial records (LP) in the 1980's were extremely well equipped, so artists could utilize cutting-edge technology of that day. In the production process of the LP records of *Geinoh Yamashirogumi*, Yamashiro/Oohashi recognized that the equalizing of high frequency components substantially higher than 20 kHz changed the intrinsic quality of the sound. It is generally accepted that audio frequencies above 20 kHz do not affect human sensory perception since these are beyond the audible range. However, highlighting frequencies higher than 50 kHz improved comfort in terms of sound perception. Yamashiro/Oohashi often used such highlights as a magical seasoning in sound production. The advent of the CD astounded him because the sound quality of a CD was decidedly inferior to that of an LP, even when produced from the identical analogue master tapes. Such knowledge led this artist to conclude that the deterioration of the sound quality arose from the limitation in the CD transmission frequency itself, i.e., the upper limitation of 22.05 kHz.

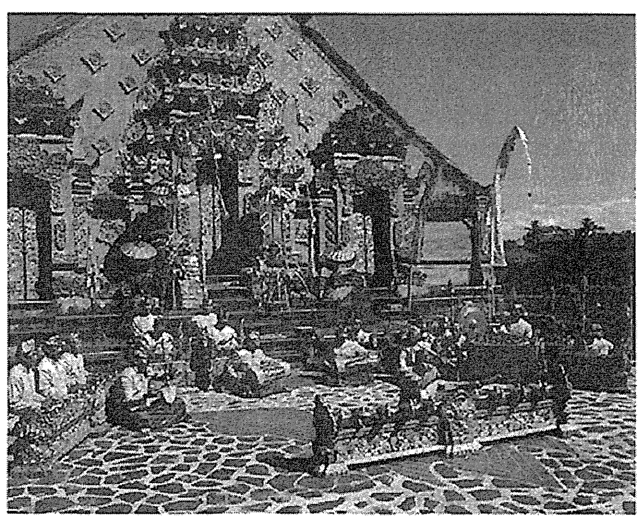

Figure 1 Balinese *gamelan* ensemble. The *gamelan* sound emitted from a CD was significantly inferior to the live sound that we heard in the village of Bali.

Several psychological experiments that evaluated sound quality subjectively by means of questionnaires, according to the recommendation of the *Comité Consultatif International Radiophonique* [1], brought home the fact that listeners did not consciously recognize the inclusion of sounds with a frequency range above 15 kHz as making any appreciable difference in sound quality. Nevertheless, and interestingly enough, artists and engineers working to produce acoustically impeccable music for commercial purposes became convinced that the intentional manipulation of high frequency components above the audible range could positively affect the perception of sound quality.

This contradiction raised the question of the maximum frequency range that might affect the perception of sound quality, which differed from the question of maximum audible frequency range. To investigate the former question, we reconsiderd experimental procedures and adopted physiological and behavioural measures, instead of the conventional CCIR (ITU-R) method, for the evaluation of high frequency components.

2. Recording and analysing of Asian traditional instrumental sounds and environmental sounds

First of all, we re-examined the frequency structure of certain musical sounds in various cultures, making use of the latest information technology. We also focused on environmental sounds, which is an important aspect of our information envirnment. To this end we developed a high definition digital sound recording system. We used B&K4939 condenser microphones to record sounds that generally have a flat frequency response of more than 100 kHz. The signals were digitally recorded on the originally developed high-speed sampling one-bit coding signal processor[2], with an A/D sampling frequency of 5.6448 MHz and multi-channel recording. This system has a generally flat frequency response greater than 150 kHz. We analyzed the recorded sounds in their frequency spectra and in the micro temporal domain through the Maximum Entropy Spectrum Array Method (MESAM), a method we developed by applying the maximum entropy method [3].

For typical musical instruments, we showed the sound structure of Balinese *gamelan*, Japanese *biwa* and *shakuhachi*, piano, flute and orchestra. We selected the environmental sounds of a tropical rainforest, which is the most likely candidate for the genetic mold of great apes and *Homo sapiens sapiens*. We went the rainforest in Java Island which has been well preserved as a UNESCO Natural Heritage site. There is limited general access to the area and noise from engines or machines is strictly prohibited. We also recorded the environmental sounds of some traditional village in Japan and Bali, and of some urban district of Tokyo by the use of the same recording system.

As the result, the range of the sound of piano, flute, orchestra and environmental sounds in urban areas was within less than 20 kHz, while the *biwa, syakuhachi, gamelan,* and rainforest sounds had a wide range, exceeding 20 kHz, the upper limit of the human audible range, even exceeding 100 kHz. The piano, flute, orchestra, and urban environmental sounds showed a simple spectral structure with small changes in the micro temporal domain. On the contrary, the *biwa, syakuhachi, gamelan,* and forest sounds show highly complex fluctuation with structural changes in the micro temporal domain of all frequency ranges, both continuous and discontinuous (Figure3). Those results were highly consistent with our previous studies [4]-[6].

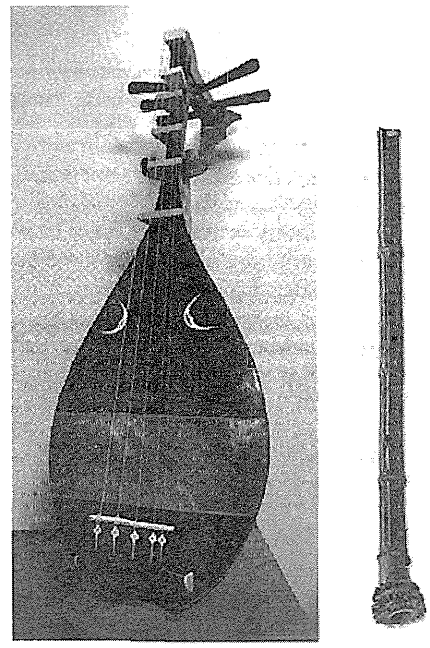

Figure 2: Japanese *biwa* and *shakuhachi*

Figure 3: The tropical rainforest

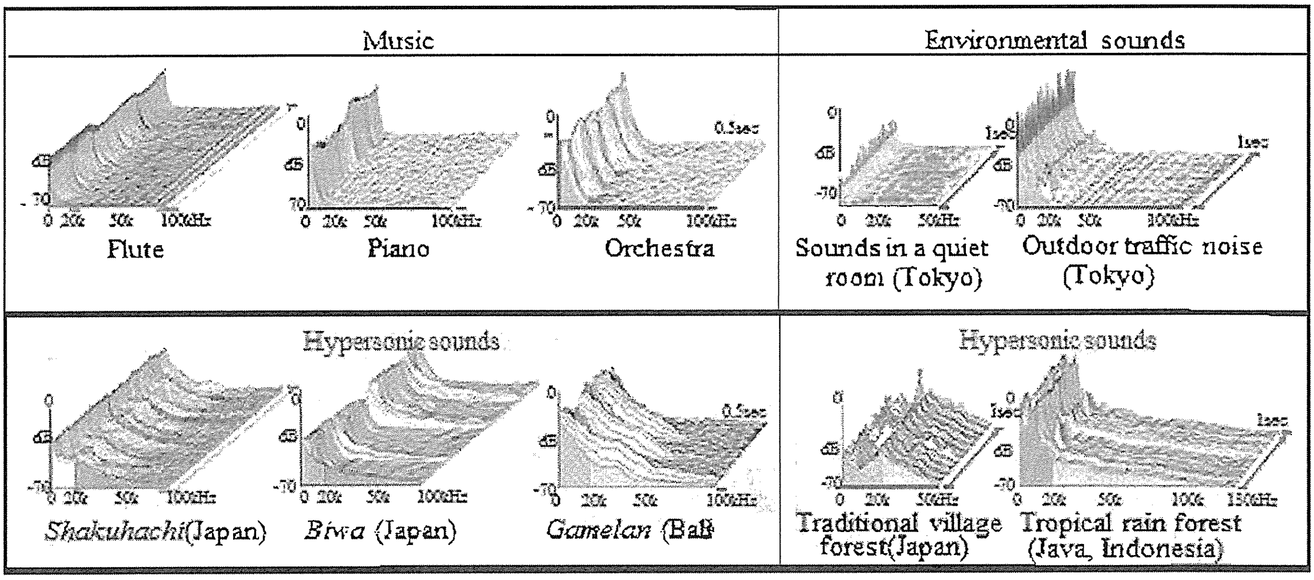

Figure 4 Sound structure of the typical musical and envirnmental sounds

3. Physiological and psychological effects of inaudible high-frequency sounds

To investigate the physiological and psychological effects of inaudible high frequency, the sound source for experiments is very important. We chose the traditional *gamelan* music of Bali for our sound source because it is natural sound containing extremely rich amounts of high frequencies with a conspicuously fluctuating structure. We developed a bi-channel sound presentation system, which enabled us to present the audible low-frequency components (LFC) and the inaudible high-frequency components (HFC) either separately or simultaneously by separately amplifing LFC and HFC and pretenting them through two independent speakers, respectively. Using this system, we demonstrated how sound data and the HFC effect on the physiological and psycological responses are transmitted to the brain.

Regional cerebral blood flow (rCBF) measured by Positron Emission Tomography (PET) and brain electrical activity were used as markers of neuronal activity, while subjects were exposed to sounds with various combinations of LFC and HFC. For a multi-parametric and statistical approach, we also measured some substances in blood indicative of immune activity and stress. Psychological and behavioral experiments were also conducted.

None of the subjects recognized the HFC as sound when it was presented by itself. Nevertheless, PET measurements revealed that, when HFC and LFC were presented together, the rCBF in the fundamental brain region including the midbrain, thalamus and hypothalamus increased significantly compared with an otherwise identical sound but lacking the HFC above 22 kHz [7].

The power spectra of the alpha frequency range of the spontaneous electroencephalogram (α-EEG) recorded from the occipital region increased with statistical significance when the subjects were exposed to sound which contained both HFC and LFC, as compared to an otherwise identical sound from which the HFC were removed (i.e., LFC alone). In contrast, as compared to the baseline, no enhancement of α-EEG was evident when either HFC or LFC was presented separately [8]. In addition, the simultaneous EEG measurements with PET showed that the power of occipital α-EEGs correlated significantly with the rCBF in the left thalamus [7].

Activation of the fundamental brain network is reflected as an increase in regional cerebral blood flow, enhancement of α-EEG, improvement of immune activity, decrease of stress-related hormones[9], perception of sound as more beautiful and pleasant in psychological experiments [8] and induction of specific behavior so as to receive a greater magnitude of sound in behavioral experiments [10]. Sound with HFCs has recently been found to improve cognitive skills [11]. (Figure 5). We call such phenomena collectively HFC, "the hypersonic effect", and we named the natural sounds including inaudible fluctuating high-frequency components the "hypersonic sound."

The fundamental brain regions activated by hypersonic sound include the neural structures related to the wide-range regulation system originating from the midbrain, especially the reward-generating system [7]. The reward-generating system includes the dopaminergic, serotoninergin, and noradrenalinergic systems that produce a desire for beauty and comfort, and a pleasure sensation when beauty and comfort are realized. Increase in the activation of these neural systems makes us feel the sensory information from the surrounding environment to be more beautiful and pleasant [8]. Since this effect is based on the physiological activation of the reward-generating system, it is likely to be universal and unlikely to depend on interests or preferences of individuals. In addition, the hypothalamus, a part of the diencephalous which constitutes part of the fundamental brain, is the highest center of the autonomic nervous system consisting of the sympathetic and parasympathetic nerves. It is, at the same time, one of the essential bases of our immune system. It focuses attention on the physiological impairment induced by the disorder and decline in brain function in these regions related to many modern diseases. Therefore, the fact that fundamental brain function can be activated by embedding hypersonic sound via media, media technology may have the potential for a novel contribution to overcoming various modern diseases caused by the disorder of fundamental brain functions. This is expected to become an application that might add new value to media communication used by all kinds of people.

And, interestingly, the hypersonic effect is induced only when HFCs are presented to the entire body surface of the subjects [12]. This suggests that biological systems other than the conventional air-conducting auditory system may likely be involved in sensing high-frequency air vibration by humans.

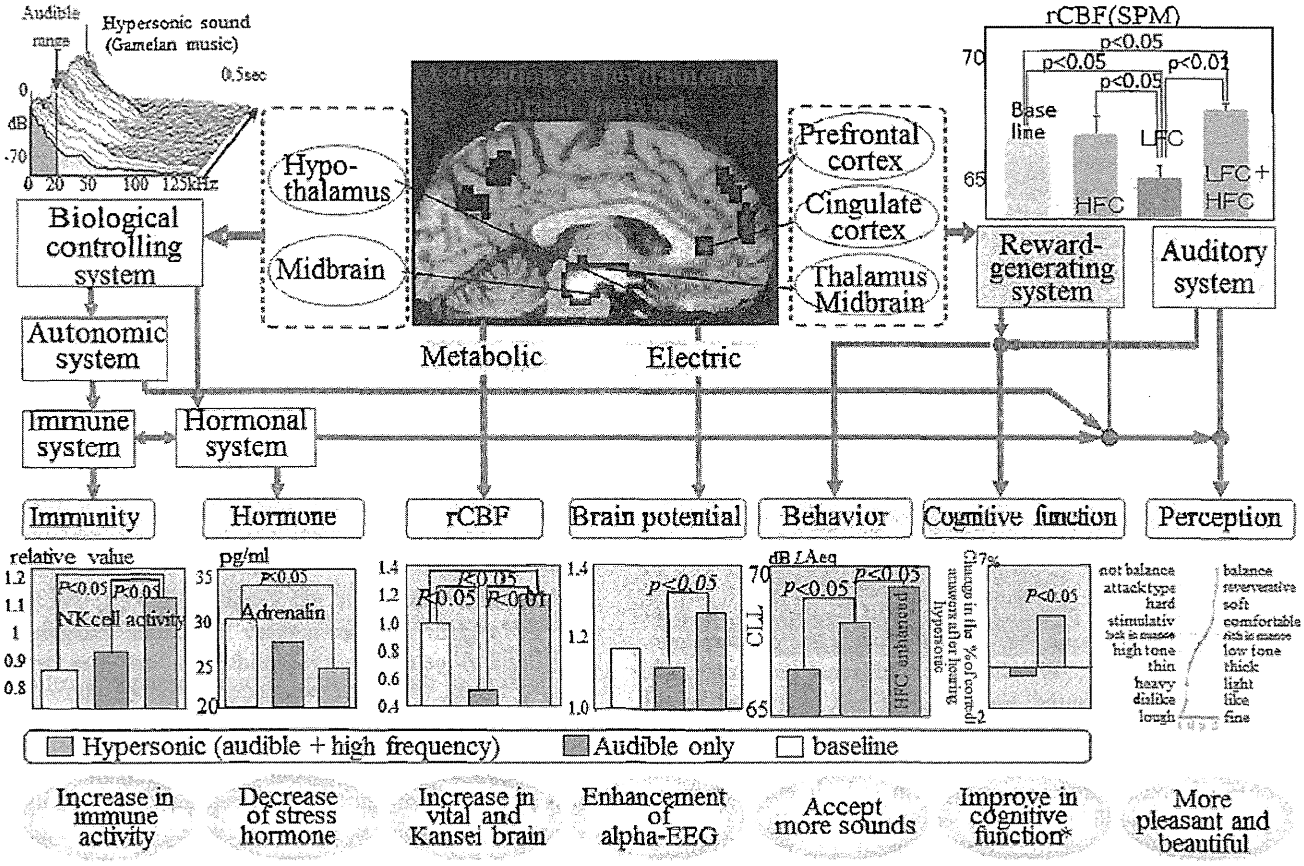

Figure 5 Overview of the hypersonic effect (Oohashi et al. 1991-2003, *Suzuki, 2013)

5. Physiological effect of high-definition 4K images

We examined the physiological effect of high-definition 4K images on the human brain using our originally developed physiological evaluation method. We developed a 4K movie (3888×2192 pixel) for this experiment using certain abstract works of Made Wianta, a famous artist of Bali. In his masterpieces, he used Balinese traditional expression of ultra fine paintings as well as modern techniques (Figure 6). In our 4K media work named "ECHOSCAPE WIANTA GALAXY", we pursued the possibility of the foremost ultra high definition visual-audio media as a tool to express ethno-arts.

Using this 4K movie as presentation material, we made certain physiological experiments [13]. We found that α2-EEG, which serves as an index of stress-free status and highly correlates with fundamental brain activity, increased with statistical significance when the subjects looked at a 4K image, as compared to a 2K image. α2-EEG was increased by full-range sound with high frequency components above 22 kHz, and decreased by sound without high frequencies, too. We observed a similar positive tendency in bioactive substances such as nor-adrenaline and cortisol. These findings suggest that the information density of a 4K format has the possibility to enhance the activity of the fundamental brain network. In addition, we found that a hypersonic sound results in a statistically significant improvement in the perception of an identical 2K video signal [14].

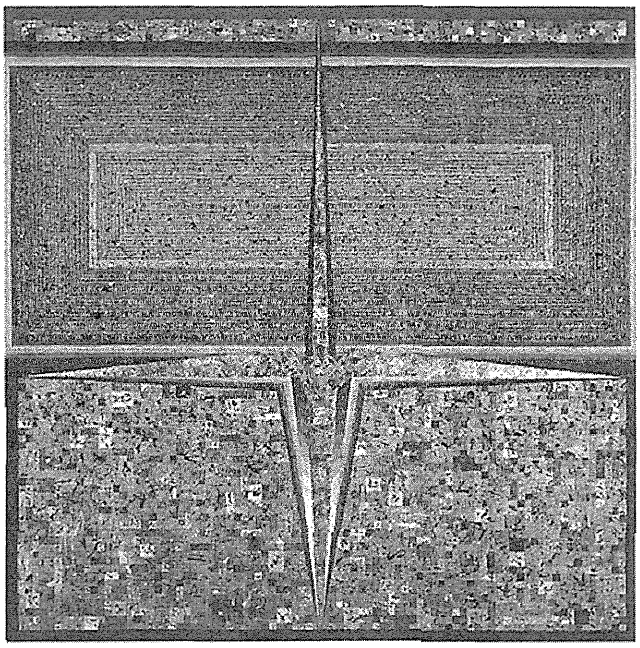

Figure 6: Painting by Made Wianta for the 4K content

6. What density format would be necessary to record and transmit the essence of Asian-Pacific performance?

The results of our human brain imaging studies indicate that sound with high-frequency components above the audible range significantly activate the entire network of the fundamental brain. This suggests that the homeostasis control system responsible for well-being as well as the reward system in the brain responsible for beauty and pleasure, are activated simultaneously. Furthermore, as a multiplier effect brought about through the activation of the fundamental brain, a variety of positive responses were revealed, such as an increase in immune activity, a decrease in stress hormones, enhancement of α-EEG, enhanced perception of beauty and pleasure, and preferential behavior with regard to the sounds engendered, and so forth. We obtained further results that point to the activation of the fundamental brain by a 4K high density image.

At the core of brain functions, the fundamental brain network resembles a computer's CPU. This mechanism includes the midbrain, thalamus and hypothalamus, all of which regulate the most basic activities of the brain. The activation of the fundamental brain network might well prevent various psychological and behavioral abnormalities as well as life-style diseases. At the same time, this comprises the center of the neural reward system that regulates the emotional response to beauty, pleasure and a sense of wonder. The activation of the brain in this manner enhances both mind and body functions and raises the level of awareness and sensitivity to stimulus response, thus creating the possibility of heightened aesthetic perception of both pleasure and beauty—not only for sound but also visually.

So, the hypersonic effect has a wide range of potential for application, from personal appreciation of music entertainment to medicine, education, urban design etc. We have pioneered the hypersonic sound system and effective content for these purposes. On the other hand, though "High resolution audio" movement has been progressing, some of the audio formats for ordinary digital audio and communication generally accepted today do not include high frequency components above the audible range, and has a possibility to decrease the activity of this essential part of the brain. Such audio formats are thus not suitable for recording and transmitting the essence of musical sounds of Asian-pacific region.

Based on these findings, we believe that the audio-visual format for digital audio should be re-evaluated not only from the viewpoint of technological possibilities but also from that of human brain reaction and cultural diversity. Moving forward, it is necessary to avoid any decreased activity of fundamental brain due to low density information in media communication, and we should also aim to bring about the transmission of high density audio-visual information in order to nurture activation of the fundamental brain. At the same time, it is equally important to overcome any cultural discrimination by sending audio-visual information of non-Western art forms and performance without diluting their essence, which possesses information density even higher than that of modern Western art, as evidenced in traditional Asian art and performance.

If we could realize an audio-visual format that could record and transmit hypersonic sound with 4K images, it could thereby activate the fundamental brain and thus contribute to the promotion of human health while augmenting the aesthetic perception of pleasure. It might also contribute to enhancing the true value of Asia-pacific performance, such as the performance of Hawaii, for people who do not live on Hawaii Island. We look forward to the time in the near future when satellite communication systems are able to transmit the essence of Asian-Pacific music and dance performance throughout our world.

Acknowledgement

This work was partly supported by JSPS through the "Funding Program for Next Generation World-Leading Researchers," initiated by the Council for Science and Technology Policy.

References

[1] CCIR Recommendation 562, 1978, 1986.

[2] Yamasaki Y. Signal processing for active control — AD/DA conversion and high speed processing, Proc. International Symposium on Active Control of Sound and Vibration, 21-32, 1991.

[3] Morimoto M. Nishina E. Yagi R. Kawai N. Nakamura S. Honda M. Maekawa T. & Oohashi T., Transcultural study on frequency and fluctuation structure of singing voices, Proc.the 18th International Congress on Acoustics, I -493-494, 2004.

[4] Oohashi T, *Oto to Bunmei* (Sound and civilization), *Iwanami Shoten, 2003.*

[5] Nishina E. Morimoto M. Yagi R. Kawai N. Nakamura

S. Honda M. Maekawa T. and Oohashi T. Structural Analysis of Musical Instrumental Sounds Based on a Biological Concept of Music, Proc. the 18th International Congress on Acoustics, I -55-58, 2004.

[6] Nishina E. Kawai N. Honda M. and Oohashi T. Design Concept of Sound Environment Based on Hypersonic Effect, The West meets the East in Acoustic Ecology, 372-380, 2006.

[7] Oohashi T. Nishina E. Honda M. Yonekura Y. Fuwamoto Y. Kawai N. Maekawa T. Nakamura S. Fukuyama H and Shibasaki H., Inaudible high-frequency sounds affect brain activity, A hypersonic effect, Journal of Neurophysiology, 83:3548-3558, 2000.

[8] Oohashi T. Nishina E. Kawai N. Fuwamoto Y and Imai H.,High Frequency Sound Above the Audible Range Affects Brain Electric Activity and Sound Perception,AES 91st Convention Preprint 3207,1991.

[9] Nishina E, Oohashi T, Physiological and psychological evaluation on the improvement of urban sound environment applying hypersonic effect, City planning review.42-3, 139-144, 2007.

[10] Yagi R. Nishina E. Honda M. and Oohashi T., Modulatory effect of inaudible high-frequency sounds on human acoustic perception. Neuroscience Letter, Vol.351, 191-195, 2003.

[11] Suzuki Y, Hypersonic effect and performance of recognition tests, KAGAKU, 83-3,343-345, 2013.

[12] Oohashi T. Kawai N. Nishina E. Honda M. Yagi R. Nakamura S. Morimoto M. Maekawa T. Yonekura Y. and Shibasaki H., The role of biological system other than auditory air-conduction in the emergence of the hypersonic effect, Brain Research, 1073-1074, 339-347, 2006.

[13] Yagi R. Nishina E. Kawai N. Tanaka K. and Oohashi T., The development of meta-perceptive media arts using ethno-arts, ETHNOART, Vol.23,169-179, 2007.

[14] Nishina E. Morimoto M. Fukusima A. and Yagi R., Hypersonic sound track for Blu-ray disc "AKIRA", ASIAGRAPH Journal, Vol.4, No.1, 53-58, 2010.

frontiers in
PSYCHOLOGY

ORIGINAL RESEARCH ARTICLE
published 28 August 2012
doi 10.3389/fpsyg.2012.00315

Abacus in the brain: a longitudinal functional MRI study of a skilled abacus user with a right hemispheric lesion

Satoshi Tanaka[1]*, Keiko Seki[2], Takashi Hanakawa[3], Madoka Harada[4], Sho K. Sugawara[5,6], Norihiro Sadato[5,6], Katsumi Watanabe[7] and Manabu Honda[3]

[1] Center for Fostering Young and Innovative Researchers, Nagoya Institute of Technology, Nagoya, Japan
[2] Graduate School of Health Sciences, Kobe University, Kobe, Japan
[3] Department of Functional Brain Research, National Institute of Neuroscience, Kodaira, Japan
[4] Department of Rehabilitation Medicine, Eisei Hospital, Hachioji, Japan
[5] Division of Cerebral Integration, National Institute for Physiological Sciences, Okazaki, Japan
[6] School of Life Sciences, The Graduate University for Advanced Studies (SOKENDAI), Hayama, Japan
[7] Research Center for Advanced Technology and Science, The University of Tokyo, Komaba, Japan

Edited by:
Joel Pearson, The University of New South Wales, Australia

Reviewed by:
David Barner, University of California San Diego, USA
Feiyan Chen, Zhejiang University, China

***Correspondence:**
Satoshi Tanaka, Center for Fostering Young and Innovative Researchers, Nagoya Institute of Technology, Gokiso-cho Showa-Ku, Nagoya 466-8555, Japan.
e-mail: tanaka.satoshi@nitech.ac.jp

The abacus, a traditional physical calculation device, is still widely used in Asian countries. Previous behavioral work has shown that skilled abacus users perform rapid and precise mental arithmetic by manipulating a mental representation of an abacus, which is based on visual imagery. However, its neurophysiological basis remains unclear. Here, we report the case of a patient who was a good abacus user, but transiently lost her "mental abacus" and superior arithmetic performance after a stroke owing to a right hemispheric lesion including the dorsal premotor cortex (PMd) and inferior parietal lobule (IPL). Functional magnetic resonance imaging experiments were conducted 6 and 13 months after her stroke. In the mental calculation task, her brain activity was shifted from the language-related areas, including Broca's area and the left dorsolateral prefrontal and IPLs, to the visuospatial-related brain areas including the left superior parietal lobule (SPL), according to the recovery of her arithmetic abilities. In the digit memory task, activities in the bilateral SPL, and right visual association cortex were also observed after recovery. The shift of brain activities was consistent with her subjective report that she was able to shift the calculation strategy from linguistic to visuospatial as her mental abacus became stable again. In a behavioral experiment using an interference paradigm, a visual presentation of an abacus picture, but not a human face picture, interfered with the performance of her digit memory, confirming her use of the mental abacus after recovery. This is the first case report on the impairment of the mental abacus by a brain lesion and on recovery-related brain activity. We named this rare case "abacus-based acalculia." Together with previous neuroimaging studies, the present result suggests an important role for the PMd and parietal cortex in the superior arithmetic ability of abacus users.

Keywords: acalculia, arithmetic, calculation, expertise, imagery, memory, plasticity, stroke

INTRODUCTION

To perform complex calculations, most people rely on physical devices such as pencil and paper, mechanical calculators, and more recently digital computers. One such device is an abacus, which is still widely used in Asian countries. The abacus is a simple device of beads and rods, and numbers are represented by the spatial locations of beads (**Figure 1**). Skilled abacus users can calculate accurate answers to mathematical problems extremely rapidly. Interestingly, however, abacus users not only manipulate the tool skillfully in its physical form but also gain the ability to mentally calculate extraordinarily large numbers, often more than 10 digits at the expert level, with unusual speed and accuracy (Hatano et al., 1977). Psychological studies have shown that a non-linguistic strategy using visual imagery of the abacus (a "mental abacus") underlies this unusual calculation ability (Hatano et al., 1977, 1987; Hatano and Osawa, 1983; Stigler, 1984; Hatta et al., 1989; Hishitani, 1990; Hanakawa et al., 2004; Tanaka et al., 2008; Frank and Barner, 2012). These works have demonstrated examples of the role of mental imagery in mental arithmetic operations.

Several behavioral and neuroimaging studies have attempted to examine the neural correlates of the calculation strategy employed by abacus users (Hatta and Ikeda, 1988; Tanaka et al., 2002, 2008; Hanakawa et al., 2003; Chen et al., 2006; Wu et al., 2009; Hu et al., 2011; Ku et al., 2012). For example, recent neuroimaging studies have reported activation in the bilateral dorsal premotor cortex (PMd) and inferior and superior parietal lobule (IPL and SPL, respectively) during mental calculation and digit memory tasks in abacus users (Tanaka et al., 2002; Hanakawa et al., 2003; Chen et al., 2006; Wu et al., 2009; Ku et al., 2012). However, there have been no neuropsychological studies that report deficits in mental abacus ability after focal brain injury. Therefore, the causal relationship between mental abacus ability and region-specific brain structures remains unclear.

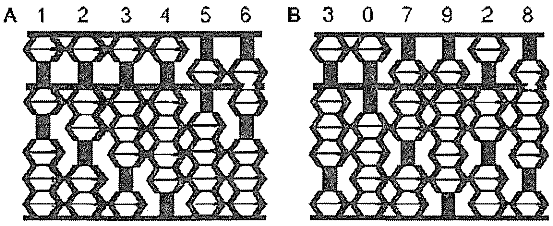

FIGURE 1 | Illustrations of an abacus. An abacus is a rectangular wooden calculator based on the decimal system. Each vertical rod has five sliding beads, one above and four below a middle horizontal bar. Numbers are represented by the configurations of the beads. A bead above the bar is equal to five when it is pushed down, and each of the four beads below is equal to one when pushed up. For example, the left figure **(A)** represents 123,456 and the right figure **(B)** represents 307,928.

Here, we report the case of a patient who was a well-experienced abacus user but had impaired mental arithmetic performance based on her mental abacus strategy due to a stroke. Her knowledge of basic arithmetic facts and her knowledge and operation of a physical abacus were intact. Only performance in mental calculation and digit memory tasks based on the mental abacus strategy was transiently impaired after the lesion. When we met her for the first time, she said "I lost my abacus in the brain."

The first purpose of the present study was to localize the lesion areas using high-resolution structural magnetic resonance imaging (MRI) with a 3T MRI scanner. We hypothesized that the lesion areas should include the PMd and/or parietal regions that were dominantly activated during the mental calculation and digit memory tasks in the previous functional MRI studies of abacus users (Tanaka et al., 2002; Hanakawa et al., 2003; Chen et al., 2006; Ku et al., 2012).

The second purpose of the present study was to examine the changes of brain activity with the recovery of mental abacus ability. Several neuroimaging studies have reported changes of brain activities with recovery from motor, attentional, or language deficits after stroke (Ward et al., 2003; Fridman et al., 2004; Corbetta et al., 2005; Price and Crinion, 2005; Heiss and Thiel, 2006). However, recovery-related changes in brain activity from deficits in arithmetic ability, especially in the non-linguistic aspects of arithmetic operation, remain totally unknown.

We hypothesized that the patient would change her strategy for mental calculation and digit memory from verbal to visuospatial with stroke recovery. Therefore, her brain activity during mental calculation would shift from language-related to visuospatial-related brain regions after recovery. As mentioned above, previous imaging studies have revealed dominant activation in the bilateral PMd, IPL, and SPL during mental calculation in abacus experts (Tanaka et al., 2002; Hanakawa et al., 2003). Neuroanatomical studies have shown that the PMd and parietal cortex have dense neuroanatomical connections (Wise et al., 1997; Luppino et al., 1999; Wise and Murray, 2000). Thus, the PMd, IPL, and SPL may work as a functional network during abacus-based mental calculation. Damage in one node may induce transient impairment of mental abacus ability. However, it is possible that the other intact nodes in the functional network could gain the ability to work without the damaged node, possibly because of functional reorganization within the remote intact nodes (Frost et al., 2003; Fridman et al., 2004; Dancause et al., 2006). Thus, we hypothesized that the intact PMd, IPL, and/or SPL would be active with the recovery of mental abacus ability.

In the present study, functional MRI experiments were conducted 6 and 13 months after her stroke and brain activity between the two sessions was compared in order to test this hypothesis. In addition, a behavioral experiment using dual-task interference paradigms was conducted to confirm her use of the mental imagery of an abacus on a digit memory task 13 months after her stroke.

MATERIALS AND METHODS

CASE REPORT

The patient was a 57-year old left handed female. She had worked as a professor in a national university before the stroke. She had a Ph.D. degree in medicine and had worked as a scientist in the field of neuropsychology for more than 25 years. She had published more than 20 international peer-reviewed papers. She had also engaged in rehabilitative medicine as a speech-language-hearing therapist for more than 25 years.

She started her abacus training at an abacus school when she was an elementary-school child, and had trained in physical and mental abacus operation for 3 years. We speculated that she was an excellent and skilled abacus user owing to the fact that she became a finalist at a domestic abacus competition in Japan in two successive years, although her training period was relatively shorter compared with the grand experts who participated in our previous functional MRI studies (Tanaka et al., 2002; Hanakawa et al., 2003). After she finished her abacus training, she kept using abacus-based mental calculation and mnemonic strategies in everyday activities for a long period and did not lose her ability. In fact, she reported that her forward digit span was around 12 before the stroke episode. This was far beyond the average score for her age group.

In July 2009, she suffered from a right hemispheric infarct in the territory of the anterior and middle cerebral arteries. When a therapist tested her digit span during a clinical neuropsychological evaluation in a hospital approximately 2 months after her stroke, she noticed that she was not able to use the mental abacus strategy for the digit span test. She was not able to generate vivid mental imagery of an abacus and the image of the abacus was very fragile. Detailed structural MRI scans were obtained in January 2010. Functional MRI scans were conducted at two different periods, the first in January 2010 and the second in August 2010.

NEUROPSYCHOLOGICAL EVALUATION

Neuropsychological evaluations were conducted approximately 1 month after stroke onset. Her score on Raven's Standard Progressive Matrices was in the average range (33/36). Similarly, her IQ measured by Kohs Block Design Test was also in the average range (108). The Standard Language Test for Aphasia (SLTA; Hasegawa et al., 1984), which has been widely used in Japan, did not detect any impairments of language. However, clinical observation detected mild impairments of her speech production: her prosody was impaired and speed of speech was slow with small volume. Clinical observation immediately after her stroke detected unilateral visual neglect. For motor function, the patient showed a severe paralysis in the left upper limb and mild paralysis in the left lower limb.

ARITHMETIC ABILITY

After her stroke onset, her arithmetic ability was not impaired according to the neuropsychological evaluation. She was able to perform four basic arithmetic operations without any problem. In fact, she was able to answer all arithmetic problems correctly in the SLTA. In addition, her long-term memory of digits was also intact because she correctly remembered the numbers of her bank accounts and airplane mileage accounts. However, she noticed that she was not able to generate visual imagery of a mental abacus, which had been easily generated before the stroke, when a neuropsychologist tested her maximum digit span 2 months after her stroke. Before the stroke, she used to use the mental abacus strategy especially when she calculated and memorized larger sequences of digits, because the visuospatial strategy, rather than a phonological strategy, was useful in coding a larger number of digits (Hatano et al., 1977; Hatano and Osawa, 1983). Due to the impairment of visual imagery after her stroke, she used the phonological strategy instead. She was able to perform four basic arithmetic operations correctly although she felt that her arithmetic ability had declined after her stroke.

Six months after her stroke, just before the first functional MRI session, we evaluated her knowledge of basic arithmetic facts, as well as her knowledge, and operation of a physical abacus. These aspects were all intact. However, she still felt that it was difficult to generate a vivid visual image of a mental abacus. She reported that she was not able to perform mental calculations and memorize digit sequences based on the mental abacus strategy because her mental abacus was fragile. However, 13 months after her stroke, she reported that her capacity for visual imagery of a mental abacus had recovered. At that time, she participated in the second functional MRI session.

Figure 2 shows her behavioral performance of maximum digit and alphabet span tasks. Forward digit span and forward and backward alphabet spans were all unchanged across the experimental period. In contrast, backward digit span improved over time after her stroke. Her backward digit span 13 months after her stroke was eight and almost equal to her forward digit span. It has been reported that abacus experts reproduce a series of digits in backward order almost as well as in the forward order, because both require experts to read off the digits from visuospatial mental representation of an abacus (Hatano and Osawa, 1983). Therefore, nearly identical maximum digit spans both backward and forward might be interpreted as evidence that she used her mental abacus 13 months after her stroke. In fact, she reported that she was able to use the mental abacus strategy for the backward digit span task 13 months after her stroke.

EXPERIMENTAL PROCEDURE

The patient gave written, informed consent before the experiments, which were approved by the local ethics committee of the National Institute for Neuroscience.

The patient participated in two functional MRI sessions of the mental calculation and digit memory tasks (Experiment 1).

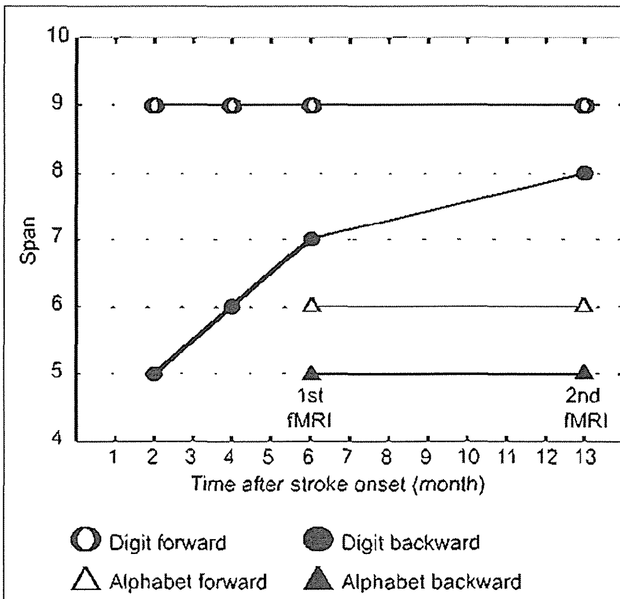

FIGURE 2 | Behavioral performance of maximum digit and alphabet span tasks. Maximum digit spans were higher compared with alphabet span, indicating that her superior performance was digit memory-specific. Her maximum forward digit span (white circle), as well as forward and backward alphabet spans (white and black triangles), was unchanged across the entire experimental period. However, the maximum backward digit span (black circle) was improved over time after her stroke.

The first and second functional MRI sessions were conducted 6 months (January 2010) and 13 months (August 2010) after her stroke onset, respectively. The difference of the brain activities between the two sessions was compared. Structural MRI scans were obtained in January 2010. In addition, the patient participated in a behavioral experiment after the second functional MRI session in order to examine whether the patient would use abacus-based mental calculation and digit memory strategies in these tasks (Experiment 2).

EXPERIMENT 1

Behavioral task in functional MRI experiment

For the functional MRI experiment, the patient performed mental calculation and digit memory tasks that were used in our previous functional MRI studies of abacus experts (Tanaka et al., 2002; Hanakawa et al., 2003). Before the functional MRI experiment, she practiced these tasks outside the scanner to become familiar with the tasks. Presentation software (Neurobehavioral Systems Inc., Albany, CA, USA) was used for the visual stimulus presentation and to record her responses. Stimuli were presented on a screen using a liquid crystal display projector, and she viewed the screen though a mirror.

For the mental calculation task, white digit stimuli were presented for 1.5 s with inter-stimulus intervals of 2 s on the center of a screen (**Figure 3A**, Hanakawa et al., 2003). Digit stimuli were presented 10 times during each trial. The patient was asked to mentally add the presented series of digits without moving her fingers. After the presentation of these digit stimuli, a red digit stimulus

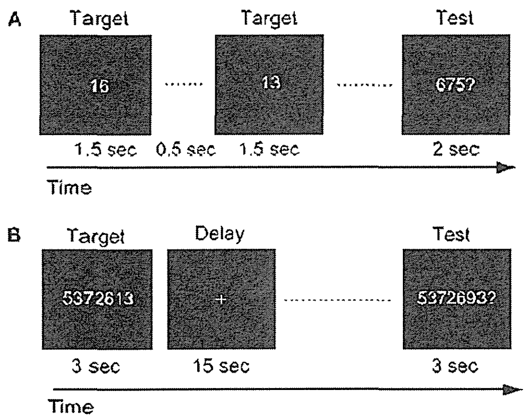

FIGURE 3 | (A) Schematic illustration of the mental calculation task. The patient was asked to add a series of numbers mentally that were visually presented on the computer screen. **(B)** Schematic illustration of the digit memory task. She was asked to retain the target sequence of digits during the delay period.

was presented for 3 s. She was asked to judge whether the addition answer in her mind and the test digit stimuli were the same or different, by pressing one of the response buttons with the right fingers. After each trial, there was an 18-s inter-trial interval (ITI) in which the patient simply watched the white fixation cross presented at the center of the screen (visual fixation condition). She performed additional tasks with single-digit and two-digit numbers. The experimental session consisted of five trials for each task in an alternate order.

For the digit memory task, a delayed match-to-sample task using a digit sequence as the stimulus was employed (**Figure 3B**, Tanaka et al., 2002). A target digit sequence was presented on the center of a screen for 3 s. The length of the digit sequence was a five digit number, which was two digits shorter than her digit span memory capacity measured before the first functional MRI session. After a 15-s delay period, during which only a fixation cross appeared on the screen, a test sequence of digits was presented for 3 s. She was asked to judge whether the target and test sequences were the same or different, by pressing one of the response buttons. Following these behavioral events, there was a 17-s visual fixation. The experimental session consisted of 10 trials.

The patient also participated in functional MRI experiments of verbal fluency and hand grip tasks 13 months after the stroke. These experiments were conducted to ascertain whether the region-specific brain activity during arithmetic tasks 13 months after the stroke would be task-specific or not. In the verbal fluency task, the subject was asked to generate in her mind as many words as possible from an indicated category (such as names of sports or fruits) during a 24-s trial. After each trial, there was a 24-s visual fixation condition. The task and fixation condition were alternately performed 10 times. In the hand grip task, the patient was asked to make the hand grip movement with her paretic hand every 2 s during a 24-s period. The hand grip task and visual fixation condition were alternately performed 10 times.

Imaging data acquisition and analysis

The functional MRI experiment was conducted using a 3.0-T MRI scanner (MAGNETOM Trio, Siemens, Erlangen, Germany). Functional images were acquired using a T2*-weighted echo planar imaging sequence (TR/TE/FA/FOV/voxel size/slice number = 3000 ms/30 ms/90°/192 mm/3.0 mm × 3.0 mm × 3.0 mm/46 axial slices for the mental calculation task, and 2000 ms/40 ms/80°/192 mm/3.0 mm × 3.0 mm × 4.0 mm/25 axial for the digit memory task). A total of 143 and 205 functional images on each mental calculation and digit memory task were collected during each session. The first three and five images of each task were discarded from data analysis to allow for the stabilization of the magnetization. Eighty-three images were obtained on each verbal fluency and hand grip task and the first three images were discarded. A high-resolution structural T1 image was acquired using a Magnetization Prepared Rapid Acquisition in Gradient Echo (MPRAGE) sequence.

SPM8 software (Wellcome Department of Cognitive Neurology, London, UK) was used for image processing and analysis. The T1 image was spatially normalized to fit a Montreal Neurological Institute (MNI) template (Evans et al., 1993). The damaged regions were masked to reduce the influence from non-brain or lesioned tissue (Brett et al., 2001). For functional images, the data were first realigned to the mean functional images in order to reduce the effect of head motion. These images were then normalized to the MNI template, with the same parameter obtained for T1 normalization. Then, the images were spatially smoothed using an isotropic Gaussian kernel of 6-mm full-width half maximum (FWHM).

Statistical analysis

Statistical analysis of the time course data at each voxel was conducted with a general linear model in order to identify voxels that showed task-specific and session-specific signal changes (Friston et al., 1994). The brain activities in the mental calculation and digit memory tasks were analyzed separately.

For the mental calculation task, one-digit and two-digit calculation tasks were separately modeled as regressors on each session with boxcar functions convolved with a hemodynamic response function. For the digit memory task, the presentations of the target and test sequences, and the delay period, were separately modeled on each session using three boxcar functions convolved with a hemodynamic response function. For the verbal fluency and hand grip task, the task period was modeled using three boxcar functions convolved with a hemodynamic response function. In all tasks, head-movement parameters were also included as regressors of no interest.

To test hypotheses about regionally specific task-effects or session-effects, the estimates for each model parameter were compared with the linear contrasts. The resulting set of voxel values constituted a statistical parametric map of the t statistic, SPM{t}. In all tasks, the statistical threshold was set at $p < 0.001$ at the voxel level. Control for multiple comparisons was achieved at the cluster level with Gaussian random field theory either in the whole brain (p corr < 0.05) or the small volume around the coordinates of the regions of interest (ROIs) based on the published papers (p svc < 0.05). On the basis of previous works on abacus experts (Tanaka et al., 2002; Hanakawa et al., 2003), spherical ROIs ($r = 8$ mm) were created at the peak voxel in the bilateral SPL (left $x = -18$, $y = -66$, $z = 60$; right $x = 14$, $y = -66$, $z = 64$ at MNI coordinate), left IPL ($x = -46$, $y = -40$, $z = 54$), left PMd ($x = -32$, $y = -6$, $z = 52$), and Broca's area ($x = -50$, $y = 10$, $z = 26$).

EXPERIMENT 2

Behavioral evaluation in mental abacus use

A behavioral experiment using interference paradigms was conducted to examine whether the patient would utilize the mental abacus strategy on a digit memory task 13 months after her stroke (**Figure 10A**). The behavioral paradigm was based on Hatta et al. (1989). She performed a delayed digit recall task. First, a target digit sequence was presented on the computer screen for 3 s. The length of the target digit sequence was eight, which was one-digit shorter than her maximum digit span memory capacity. After a 15-s retention interval, she was asked to recall and report the digit sequence orally. There were three experimental conditions which differed according to the types of visual distractors. Pictures of abacus figures, human faces, or gray rectangles were presented on the center of the screen during the retention interval. Each distractor stimulus was presented for 1 s with 0.5 s inter-stimulus intervals. She performed 15 trials for each distractor condition. We hypothesized that if she utilized a mental abacus for the digit memory task, the presentation of the pictures of abacus figures would interfere with task performance more than the presentation of the human faces and gray rectangles.

RESULTS

STRUCTURAL MRI

The T1-weighted MRI showed a right fronto-parietal lesion, involving the posterior parts of the inferior and superior frontal gyrus, anterior insula, anterior cingulate gyrus, pre and post central gyrus, and supramarginal gyrus (**Figure 4**). These lesioned areas included the right PMd and IPL, which were dominantly activated during the mental calculation and digit memory tasks in the previous functional MRI studies of abacus experts (Tanaka et al., 2002; Hanakawa et al., 2003; Chen et al., 2006; Ku et al., 2012). The lesion was not observed in the left hemisphere.

EXPERIMENT 1: FUNCTIONAL MRI EXPERIMENT

Mental calculation task

The patient responded correctly in all trials of the calculation tasks in both functional MRI sessions. **Figure 5A** shows brain activity associated with one- and two-digit mental calculation tasks relative to the visual fixation condition (see **Table A1** in Appendix online). In one-digit mental calculations, brain activity was generally lateralized to the left hemisphere both 6 and 13 months after her stroke. In contrast, brain activity in two-digit mental calculations was observed bilaterally both 6 and 13 months after her stroke. These brain regions include the middle frontal gyrus, pre- and postcentral gyrus, SPL, middle and superior occipital gyrus, inferior temporal gyrus, and cerebellum. This activity was not observed in the damaged regions of the right hemisphere. When brain activities during one- and two-digit mental calculation tasks were directly compared, significant brain activity in the left middle frontal gyrus was observed 6 months after her stroke (**Figure 5B**). In contrast, significant activity was observed in the bilateral SPL, right middle frontal gyrus, postcentral gyrus, and middle occipital gyrus 13 months after her stroke.

To investigate the time-specific brain activities, her whole brain activities between 6 and 13 months after her stroke were directly compared. A previous study has revealed that the region-specific brain activities in abacus users were more evident in the mental calculation task with a higher cognitive demand (Hanakawa et al., 2003). Therefore, the brain activities in the two-digit addition task between 6 and 13 months after her stroke were compared in the analysis.

The results are shown in **Figure 6**. The left hemispheric cortical activities including Broca's area (peak coordinate $x = -48$, $y = 8$, $z = 8$; $t = 4.73$, cluster size = 227 voxels, p corr < 0.05), the left dorsolateral prefrontal cortex (DLPFC, $x = -48$, $y = 38$, $z = 30$; $t = 4.81$, cluster size = 118 voxels, p corr < 0.05), and IPL ($x =\ \ 44$, $y =\ \ 50$, $z = 54$; $t = 4.38$, cluster size = 118 voxels, p corr < 0.05) were significantly greater at 6 months compared with 13 months after the stoke (**Figure 6A**). These brain regions were repeatedly activated in many language- related cognitive tasks (Paulesu et al., 1993; Fiez et al., 1996; Smith et al., 1998). In contrast, activity in the left SPL ($x = -20$, $y = -66$, $z = 66$; $t = 3.60$, cluster size = 10, p svc < 0.05) was significantly greater at 13 months compared with 6 months after her stroke

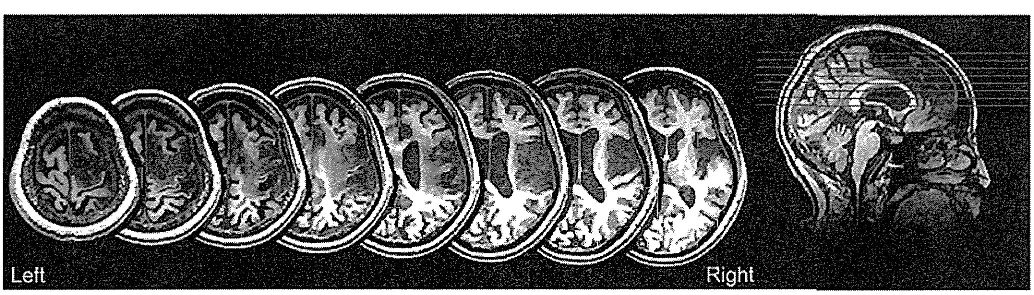

FIGURE 4 | T1-weighted structural MRI of the patient. The lesion was observed in the fronto-parietal cortex, including the posterior parts of the inferior and superior frontal gyrus, anterior insula, anterior cingulate gyrus, pre and post central gyrus, and supramarginal gyrus. No lesion was observed in the left hemisphere

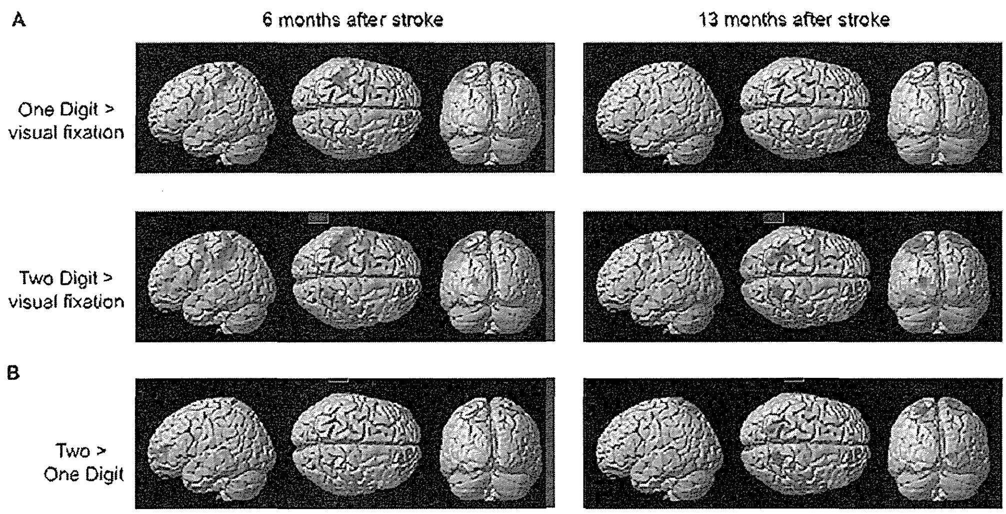

FIGURE 5 | (A) Active areas during the mental calculation task relative to those during the visual fixation condition 6 and 13 months after her stroke. **(B)** Active areas during the two-digit mental calculation task relative to those during the one-digit task 6 and 13 months after her stroke. The blue region indicates the lesion area. Brain activity is overlayed on the spatially normalized rendering images (voxel level, $p < 0.001$ uncorrected for multiple comparison, cluster level $p < 0.05$ FWE). The detailed coordinates and statistical values are listed in **Table A1** in Appendix online.

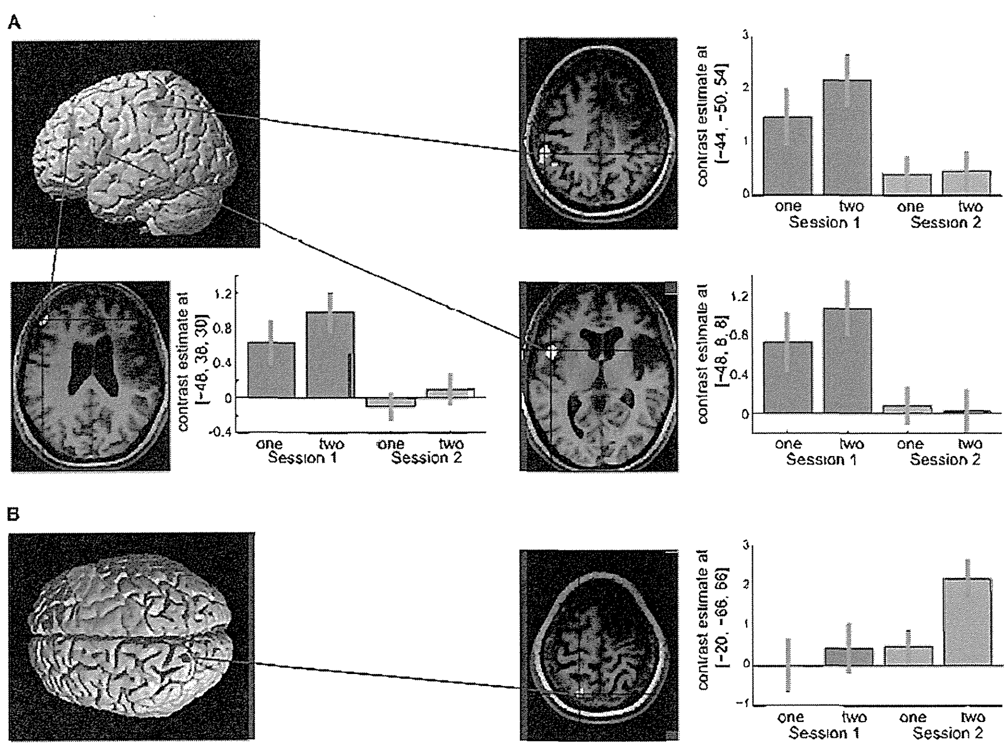

FIGURE 6 | (A) Active areas during the mental calculation task-specific to 6 months after her stroke. These areas include Broca's area, the left dorsolateral prefrontal cortex and the inferior parietal cortex. **(B)** Active areas specific to 13 months after her stroke. Only the left superior parietal cortex was significantly activated on this comparison. The blue color on the rendering structural image indicates the damaged cortical area. Only statistically significantly different activity is shown (voxel level, $p < 0.001$ uncorrected for multiple comparison; cluster level $p < 0.05$ FWE). In each bar graph, the vertical axis indicates contrast estimated values relative to the baseline, whereas the horizontal axis indicates the type of task. One and two in the figure indicates one-digit and two-digit addition task, respectively. Blue and orange color bar indicates session 1 and 2, respectively. The error bars represent standard deviations across scans.

(**Figure 6B**). Activity in the left SPL was observed in the previous functional imaging studies of mental calculation tasks in abacus experts (Hanakawa et al., 2003; Chen et al., 2006; Wu et al., 2009). These functional MRI results were very consistent with the patient's subjective report that she was able to shift the calculation strategy from a phonological – based to a mental abacus – based strategy according to her level of recovery from the stroke.

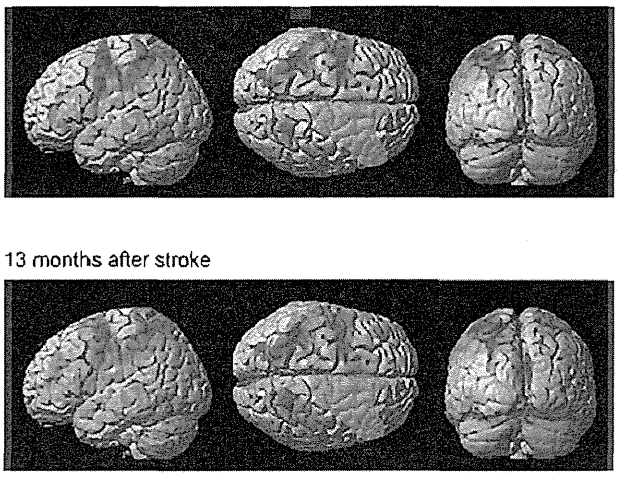

FIGURE 7 | Active areas during the delay period on the digit memory task relative to these during the visual fixation condition 6 and 13 months after her stroke. The blue region indicates the lesion area. Brain activity is overlayed on the spatially normalized rendering images (voxel level, $p < 0.001$ uncorrected for multiple comparison, cluster level $p < 0.05$ FWE) The detailed coordinates and statistical values are listed in **Table A2** in Appendix online.

Digit memory task

The patient correctly answered all trials in both functional MRI sessions. The present analysis of the digit memory task focuses on the brain activities associated with memory retention and thus the brain activities only during the delay period are reported. **Figure 7** shows brain activity associated with the delay interval period during the digit memory tasks relative to the visual fixation condition (see **Table A2** in Appendix online). Overall, brain activity was left lateralized 6 months after her stroke, whereas bilateral activation was observed 13 months after her stroke. These brain regions include the inferior and middle frontal gyrus, insula, supplementary motor area, IPL, SPL, cuneus, fusiform gyrus, inferior temporal gyrus, and cerebellum.

A direct comparison of the brain activities observed during the delay period between the two sessions is shown in **Figure 8**. No brain regions were observed that showed significant regional-specific activities at 6 months compared with those at 13 months after her stroke. In contrast, activities in the bilateral SPL (left $x = -18$, $y = -64$, $z = 64$; $t = 6.36$, cluster size = 223, p corr < 0.05; right $x = 20$, $y = -48$, $z = 70$; $t = 4.93$, cluster size = 132, p corr < 0.05) and the right visual association cortex ($x = 36$, $y = -80$, $z = -14$; $t = 6.77$, cluster size = 529, p corr < 0.05) were significantly greater at 13 months compared with 6 months after her stroke. The bilateral activities in the SPL during the delay period were observed in the previous functional MRI study of abacus experts (Tanaka et al., 2002). Thus, the result suggests that the visuospatial strategy of mental abacus representation might be more dominantly used in the digit memory task,

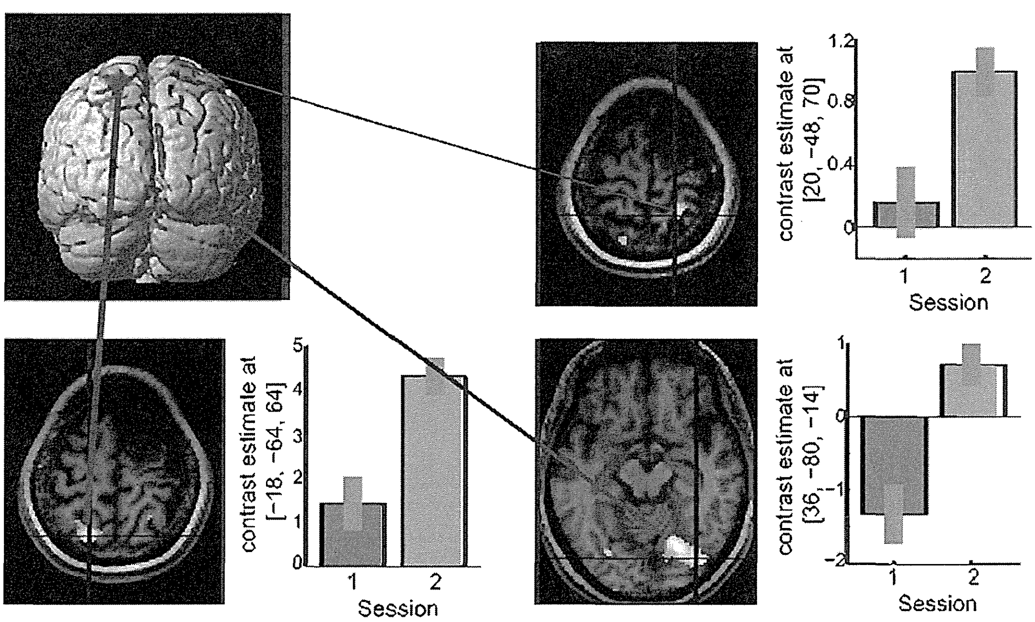

FIGURE 8 | Active areas during the retention period in the digit memory task specific to 13 months after her stroke. The bilateral superior parietal lobule and visual association cortex were significantly activated. Statistical threshold was the same as with the mental calculation task.

the same as in the mental calculation task, at 13 months after her stroke. Again, this was consistent with the patient's subjective report that she was able to utilize the mental abacus strategy 13 months after her stroke.

Verbal fluency and hand grip tasks

Figure 9 shows the results of verbal fluency and hand grip tasks. There was significant task-specific activity mainly in the left DLPFC for the verbal fluency task and in the right primary motor cortex for the left hand grip task, respectively. In contrast, in both tasks, the left SPL, which was dominantly activated during her mental calculation and digit memory tasks, was not significantly activated compared with the visual fixation condition. These findings suggest that activation in the SPL was specific to mental calculation and digit memory tasks 13 months after the stroke.

EXPERIMENT 2

Behavioral experiment

The number of correctly answered trials was 12 for the human face and gray rectangle conditions, compared with 6 for the abacus picture condition (Figure 10B). Therefore, the number of the correct trials in the abacus picture condition was clearly fewer than that in the other two distractor conditions. This result showed that the presentation of pictures of abacus figures interfered with the patient's task performance, suggesting her use of a mental abacus on the digit memory task and mental calculations 13 months after her stroke.

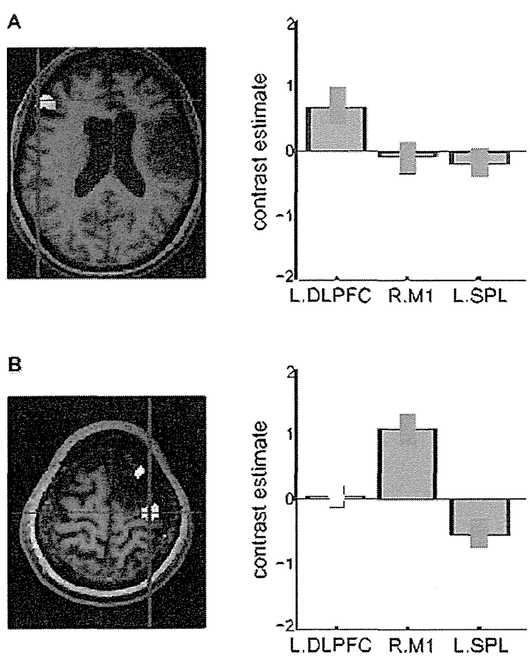

FIGURE 9 | Active areas during verbal fluency and left hand grip tasks 13 months after the stroke. (A) There were significant task-specific activities in the left dorsolateral prefrontal cortex (DLPFC) for verbal fluency task and **(B)** right primary motor cortex (M1) for left hand grip task. The left SPL was not significantly activated. In each bar graph, the vertical axis indicates contrast estimated values relative to the visual fixation task, whereas the horizontal axis indicates each brain region. The error bars represent standard deviations across scans.

DISCUSSION

This is the first case report on the impairment of mental abacus ability by a brain lesion and on recovery-related brain activity. The patient's knowledge and operation of basic arithmetic facts and of a physical abacus were all intact. Her impairment of arithmetic ability was specific to mental calculation and digit memory only based on the mental abacus strategy. Therefore, we consider that this would be a specific case of spatial acalculia (Hecaen et al., 1961; Hartje, 1987; Granà et al., 2006). This is a quite rare case and we have named this "abacus-based acalculia."

The results of the present study show that brain activity during mental calculation at 13 months after her stroke was observed more in an area implicated in visuospatial working memory (Jonides et al., 1993; Mellet et al., 1996; Courtney et al., 1998a,b; Rowe et al., 2001; Tanaka et al., 2005; Oshio et al., 2010), whereas at 6 months after her stroke, brain activity was more predominant in the left hemisphere in areas related to verbal working memory (Paulesu et al., 1993; Fiez et al., 1996; Smith et al., 1998). Brain activity at 13 months after her stroke was observed in the left SPL, whereas that at 6 months after her stroke was observed in Broca's area and the left DLPFC and IPL. This shift of region-specific brain activities is consistent with her subjective report that she was able to shift her calculation strategy from a verbal to a visuospatial strategy according to the level of her recovery from the stroke. In a behavioral experiment using interference paradigms, a visual presentation of an abacus picture, but not a human face picture, interfered with her performance of digit memory, confirming her use of the mental abacus 13 months after her stroke.

The present result is consistent with previous functional imaging studies that reported activation in the SPL during mental calculation and digit memory tasks in abacus users (Tanaka et al., 2002; Hanakawa et al., 2003; Chen et al., 2006; Wu et al., 2009). It is possible that a spatial representation of numbers is developed through abacus practice, which involves rule based visuo motor processing, and utilized in mental calculation and digit memory tasks, because it is more efficient to mentally manipulate large numbers using a spatial representation than a sequentially organized phonological representation (Hatano et al., 1977; Hatano and Osawa, 1983 Hatano et al., 1987; Hatta et al., 1989; Hishitani, 1990; Tanaka et al., 2008; Frank and Barner, 2012). The SPL might be a key brain region for such non-verbal visuospatial representation of numbers.

According to the structural MRI, the lesion area involved the right fronto-parietal regions. Her impairment of mental abacus ability due to her right hemispheric lesion was consistent with previous behavioral and neuroimaging studies that indicate involvement of the right hemisphere in the superior arithmetic abilities of abacus users (Hatta and Ikeda, 1988; Tanaka et al., 2002; Hanakawa et al., 2003; Chen et al., 2006; Wu et al., 2009). More specifically, her lesion area included the right PMd and IPL, which have been repeatedly activated in the previous functional neuroimaging studies of abacus users (Tanaka et al., 2002; Hanakawa

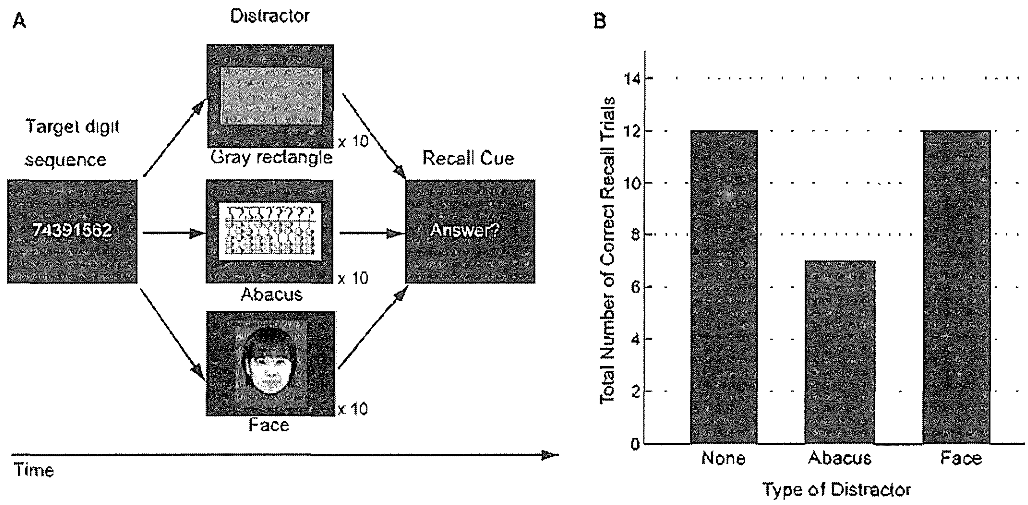

FIGURE 10 | (A) A delayed digit recall task using interference paradigms, based on Hatta et al. (1989). The patient was asked to recall a target digit sequence after a 15-s retention interval. Three different types of visual distractors were presented during the retention interval (pictures of abacus figures, human faces, or gray rectangles). **(B)** Behavioral performance in the delayed digit recall task. The number of correctly answered trials was 12 when a human face or a gray rectangle were presented as distractors. In contrast, the number of correctly answered trials was six when the distractor was pictures of abacus figures. This result indicated that the presentation of abacus figures interfered with the patient's digit memory performance.

et al., 2003; Chen et al., 2006; Wu et al., 2009). Therefore, the present study may suggest the functional relevance of these brain regions to the mental calculation and digit memory of abacus users. However, we should be careful about such interpretations because the lesion area not only covered the PMd and IPL but also included relatively large areas of the right frontal and parietal cortex. A non-invasive brain stimulation study or neuropsychological study of patients with a more focal brain lesion will clarify this issue.

The activation in the SPL was less evident at 6 months compared with 13 months after her stroke. This implies that the damaged regions in the right hemisphere, possibly the PMd and IPL, and the SPL may work as a functional network during abacus-based mental calculation and digit memory. In fact, it is known that there is an anatomical and functional connectivity between the premotor and parietal cortex (Wise et al., 1997; Luppino et al., 1999; Wise and Murray, 2000; Tanaka et al., 2005; Oshio et al., 2010). Damage in one cortical node may induce less activity in another cortical node within the functional network. However, 13 months after her stroke, the SPL might be able to work without the damaged brain regions, possibly because of remote cortical reorganization that may occur within the intact SPL region (Frost et al., 2003; Fridman et al., 2004; Dancause et al., 2006).

In the present study, the significant activity in the SPL was left lateralized in the mental calculation task, whereas bilateral activation was found in the digit memory task. This might be due to differences in task difficulty between the two tasks, based on her subjective report after the experiment. A previous functional MRI study has reported that bilateral SPL activity in abacus users was more evident in the tasks with a higher cognitive demand (Hanakawa et al., 2003). In fact, if a lower statistical threshold was used in the mental calculation task, activation in the bilateral SPL was observed.

Regarding the task-specific activity of the SPL, one might argue that the observed differences in SPL activity among arithmetic and other control tasks (such as verbal fluency and hand grip) might be explained by the difference in task difficulty. However, that would be unlikely because the SPL activity during verbal fluency and hand grip tasks was not significantly different compared with the easiest visual fixation condition in which the subject simply watched the fixation on the screen. If the explanation of activity difference by task difficulty is true, then SPL activity during the verbal fluency and hand grip tasks should be greater than during the visual fixation task. Therefore, it is reasonable to consider that the SPL activity would be specific for her mental abacus use after her stroke recovery.

It has been proposed that the human capacity for mathematical intuition depends on both linguistic competence and visuospatial representations (Dehaene et al., 1999). By a combination of neuropsychological and neuroimaging techniques, the present finding provides evidence for an important role of visual imagery in mental arithmetic operations and also for its underlying neural correlates, the superior parietal cortex. The SPL might be an important cortical structure for non-verbal forms of number representation for calculation. The present finding may contribute to developing our understanding of the relationship between mental imagery and mental arithmetic operations.

There are several limitations for this study. First, this is a single case study and it is difficult to generalize this finding to other populations. Second, the patient was left handed and thus it is difficult to discuss the lateralization of brain activation. For this reason, we did not make any conclusions on the lateralization of brain activity from the present study. Third, the results of the behavioral interference task might be explained by a potential difference in difficulty between the distractors, such as the difference in the visual complexity of stimuli. Thus, in future studies, interference tasks should be matched for difficulty and the subject should be asked to make a behavioral response to the interfering stimuli, to be certain that the subject is actually processing the stimuli. Despite these limitations, however, we believe that this result has important implications regarding the neural substrates underlying the superior arithmetic ability of abacus users, because this is the first neuropsychological case report and also the first longitudinal functional MRI study of abacus users.

In conclusion, the present study reports for the first time a case of "abacus-based acalculia" caused by a brain lesion. Together with previous neuroimaging studies, the present result provides evidence for an important role of the PMd and parietal cortex in the mental calculation and digit memory tasks of abacus users.

ACKNOWLEDGMENTS

This work was supported by grants from the Grants-in-Aid for Scientific Research (KAKENHI) to Satoshi Tanaka (24680061).

REFERENCES

Brett, M., Leff, A. P., Rorden, C., and Ashburner, J. (2001). Spatial normalization of brain images with focal lesions using cost function masking. *Neuroimage* 14, 486–500.

Chen, F., Hu, Z., Zhao, X., Wang, R., Yang, Z., Wang, X., and Tang, X. (2006). Neural correlates of serial abacus mental calculation in children: a functional MRI study. *Neurosci. Lett.* 403, 46–51.

Corbetta, M., Kincade, M. J., Lewis, C., Snyder, A. Z., and Sapir, A. (2005). Neural basis and recovery of spatial attention deficits in spatial neglect. *Nat. Neurosci.* 8, 1603–1610.

Courtney, S. M., Petit, L., Haxby, J. V., and Ungerleider, L. G. (1998a). The role of prefrontal cortex in working memory: examining the contents of consciousness. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 353, 1819–1828.

Courtney, S. M., Petit, L., Maisog, J. M., Ungerleider, L. G., and Haxby, J. V. (1998b). An area specialized for spatial working memory in human frontal cortex. *Science* 279, 1347–1351.

Dancause, N., Barbay, S., Frost, S. B., Zoubina, E. V., Plautz, E. J., Mahnken, J. D., and Nudo, R. J. (2006). Effects of small ischemic lesions in the primary motor cortex on neurophysiological organization in ventral premotor cortex. *J. Neurophysiol.* 96, 3506–3511.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., and Tsivkin, S. (1999). Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science* 284, 970–974.

Evans, A. C., Collins, D. L., Mills, S. R., Brown, E. D., Kelly, R. L., and Peters, T. M. (1993). 3D statistical neuroanatomical models from 305 MRI volumes. *IEEE Nucl. Sci. Symp. Conf. Rec.* 108, 1877–1878.

Fiez, J. A., Raife, E. A., Balota, D. A., Schwarz, J. P., Raichle, M. E., and Petersen, S. E. (1996). A positron emission tomography study of the short-term maintenance of verbal information. *J. Neurosci.* 16, 808–822.

Frank, M. C., and Barner, D. (2012). Representing exact number visually using mental abacus. *J. Exp. Psychol. Gen.* 141, 134–149.

Fridman, E. A., Hanakawa, T., Chung, M., Hummel, F., Leiguarda, R. C., and Cohen, L. G. (2004). Reorganization of the human ipsilesional premotor cortex after stroke. *Brain* 127, 747–758.

Friston, K. J., Holmes, A. P., Worsley, K. J., Poline, J. P., Frith, C. D., and Frackowiak, R. S. J. (1994). Statistical parametric maps in functional imaging: a general linear approach. *Hum. Brain. Mapp.* 2, 189–210.

Frost, S. B., Barbay, S., Friel, K. M., Plautz, E. J., and Nudo, R. J. (2003). Reorganization of remote cortical regions after ischemic brain injury: a potential substrate for stroke recovery. *J. Neurophysiol.* 89, 3205–3214.

Granà, A., Hofer, R., and Semenza, C. (2006). Acalculia from a right hemisphere lesion dealing with "where" in multiplication procedures. *Neuropsychologia* 14, 2972–2986.

Hanakawa, T., Honda, M., and Hallett, M. (2004). Amodal imagery in rostral premotor areas. *Behav. Brain Sci.* 27, 406–407.

Hanakawa, T., Honda, M., Okada, T., Fukuyama, H., and Shibasaki, H. (2003). Neural correlates underlying mental calculation in abacus experts: a functional magnetic resonance imaging study. *Neuroimage* 19, 296–307.

Hartje, W. (1987). "The effect of spatial disorders on arithmetical skills," in *Mathematical disabilities: a cognitive neuropsychological perspective*, eds G. Deloche, and X. Seron (Hillsdale, NJ: Erlbaum), 121–125.

Hasegawa, T., Kishi, H., Shigeno, K., Tanemura, J., Kusunoki, K., Kifune, Y., and Yoshida, M. (1984). A study on aphasia rating scale: a method for overall assessment of SLTA results. *High. Brain Funct. Res.* 4, 638–646.

Hatano, G., Amaiwa, S., and Shimizu, K. (1987). Formation of a mental abacus for computation and its use as a memory devices for digits: a developmental study. *Dev. Psychol.* 23, 832–838.

Hatano, G., Miyake, Y., and Bink, M. (1977). Performance of expert abacus operators. *Cognition* 5, 57–71.

Hatano, G., and Osawa, K. (1983). Digit memory of grand experts in abacus-derived mental calculation. *Cognition* 15, 95–110.

Hatta, T., Hirose, T., Ikeda, K., and Fukuhara, H. (1989). Digit memory of soroban experts: evidence of utilization of mental imagery. *Appl. Cogn. Psychol.* 3, 23–33.

Hatta, T., and Ikeda, K. (1988). Hemispheric specialization of abacus experts in mental calculation: evidence from the results of time-sharing tasks. *Neuropsychologia* 26, 877–893.

Hécaen, H., Angerlergues, R., and Houiller, S. (1961). Les variétés cliniques des acalculies au cours des lésions rétrorolandiques: approche statistique du problème *Rev. Neurol. (Paris)* 105, 85–103.

Heiss, W. D., and Thiel, A. (2006). A proposed regional hierarchy in recovery of post-stroke aphasia. *Brain. Lang.* 98, 118–123.

Hishitani, S. (1990). Imagery expert: how do expert abacus operators process imagery? Appl. *Cogn. Psychol.* 4, 33–46.

Hu, Y., Geng, F., Tao, L., Hu, N., Du, F., Fu, K., and Chen, F. (2011). Enhanced white matter tracts integrity in children with abacus training. *Hum. Brain Mapp.* 32, 10–21.

Jonides, J., Smith, E. E., Koeppe, R. A., Awh, E., Minoshima, S., and Mintun, M. A. (1993). Spatial working memory in humans as revealed by PET. *Nature* 363, 623–625.

Ku, Y., Hong, B., Zhou, W., Bodner, M., and Zhou, Y. D. (2012). Sequential neural processes in abacus mental addition: an EEG and FMRI case study. *PLoS ONE* 7, e36410. doi:10.1371/journal.pone.0036410

Luppino, G., Murata, A., Govoni, P., and Matelli, M. (1999). Largely segregated parietofrontal connections linking rostral intraparietal cortex (areas AIP and VIP) and the ventral premotor cortex (areas F5 and F4). *Exp. Brain Res.* 128, 181–187.

Mellet, E., Tzourio, N., Crivello, F., Joliot, M., Denis, M., and Mazoyer, B. (1996). Functional anatomy of spatial mental imagery generated from verbal instructions. *J. Neurosci.* 16, 6504–6512.

Oshio, R., Tanaka, S., Sadato, N., Sokabe, M., Hanakawa, T., and Honda, M. (2010). Differential effect of double-pulse TMS applied to dorsal premotor cortex and precuneus during internal operation of visuospatial information. *Neuroimage* 49, 1108–1115.

Paulesu, E., Frith, C. D., and Frackowiak, R. S. (1993). The neural correlates of the verbal component of working memory. *Nature* 362, 342–345.

Price, C. J., and Crinion, J. (2005). The latest on functional imaging studies of aphasic stroke. *Curr. Opin. Neurol.* 18, 429–434.

Rowe, J., Toni, I., Josephs, O., Frackowiak, R. S., and Passingham, R. E. (2001). The prefrontal cortex: response selection or maintenance within eorking memory? *Science* 288, 1656–1660.

Smith, E. E., Jonides, J., Marshuetz, C., and Koeppe, R. A. (1998). Components of verbal working memory: evidence from neuroimaging. *Proc. Natl. Acad. Sci. U.S.A.* 95, 876–882.

Stigler, J. (1984). "Mental abacus": the effects of abacus training on Chinese children's mental calculation. *Cogn. Psychol.* 16, 145–176.

Tanaka, S., Hanakawa, T., and Honda, M. (2008). Neural substrates underlying cognitive expertise. *Brain Nerve* 60, 257–262.