J Med Dent Sci 2004; 51: 147－154

Original Article

Comparison of fMRI Data Analysis by SPM99 on Different Operating Systems

Hideo Shinagawa[1], Ei-ichi Honda[2], Takashi Ono[1], Tohru Kurabayashi[2] and Kimie Ohyama[1]

1) Maxillofacial Orthognathics and 2) Oral and Maxillofacial Radiology, Graduate School, Tokyo Medical and Dental University

The hardware chosen for fMRI data analysis may depend on the platform already present in the laboratory or the supporting software. In this study, we ran SPM99 software on multiple platforms to examine whether we could analyze fMRI data by SPM99, and to compare their differences and limitations in processing fMRI data, which can be attributed to hardware capabilities. Six normal right-handed volunteers participated in a study of hand-grasping to obtain fMRI data. Each subject performed a run that consisted of 98 images. The run was measured using a gradient echo-type echo planar imaging sequence on a 1.5T apparatus with a head coil. We used several personal computer (PC), Unix and Linux machines to analyze the fMRI data. There were no differences in the results obtained on several PC, Unix and Linux machines. The only limitations in processing large amounts of the fMRI data were found using PC machines. This suggests that the results obtained with different machines were not affected by differences in hardware components, such as the CPU, memory and hard drive. Rather, it is likely that the limitations in analyzing a huge amount of the fMRI data were due to differences in the operating system (OS).

Corresponding Author: Hideo Shinagawa
Maxillofacial Orthognathics, Graduate School,
Tokyo Medical and Dental University
5-45, Yushima 1-chome, Bunkyo-Ku, Tokyo, 113-8549, Japan
TEL: (+81)-3-5803-5537
FAX: (+81)-3-5803-0203
E-mail: h-shinagawa.mort@tmd.ac.jp
Received May 6; Accepted June 11, 2004

Key words: fMRI, data analysis, personal computer, workstation, operating system

Introduction

Over the past two decades, the functional magnetic resonance imaging (fMRI) technique, which takes advantage of the blood oxygenation level-dependent (BOLD) effect[1-5], has become an important non-invasive tool for identifying cerebral cortical representations that correlate with a variety of motor tasks including movements of the finger[6] and tongue[7,8] as well as sensory processing, such as of auditory[9], visual[10] and taste[11] stimuli. BOLD-fMRI has been used to determine the cortical activation foci that are related to highly organized cognitive function. This technique has also been exploited for the clinical analysis of pathological neuronal networks such as in epilepsy, schizophrenia and Alzheimer disease.

Many software packages for analyzing fMRI data[12] are commercially available. These include AFNI (Analysis of Functional NeuroImages, http://varda.biophysics.mcw.edu), BrainVoyager (Brain innovation B.V., http://www.brainvoyager.de), SPM (Statistical Parametric Mapping, http://www.fil.ion.bpmf.ac.uk/spm), and MEDx (Medical Numerics, Inc., http://www.sensor.com). SPM refers to the construction and assessment of a spatially extended statistical process to test hypotheses about neuroimaging data obtained from positron emission tomography and fMRI. The SPM approach is based on the voxel: images are spatially normalized into a standard space and smoothed. Parametric statistical models are assumed in each voxel, using the general linear model to describe the variability in data in terms of experimental and confounding effects, and residual variability. Hypotheses expressed in terms of model parameters are assessed in each voxel with univariate statistics. Problems derived from multiple comparisons that assess all of the voxel statistics simultaneously are addressed using the theory of continuous random fields, assuming that the statistical image is a good lattice representation of an underlying continuous stationary random field. Results for the Euler characteristic lead to corrected p-values for each voxel hypothesis. In addition, this theory permits the computation of corrected p-values for clusters of voxels that exceed a given threshold and for entire sets of supra-threshold clusters, leading to more powerful statistical tests at the expense of some localizing power. SPM software is available for Windows 95/98/NT and the Unix and Linux operating system (OS) /platform, but not for Windows (e.g., 2000, XP and Me), Mac OS or client OS. SPM software is affinitive to MATLAB (The MathWorks, inc., http://www.mathworks.com/) functions and subroutines implementing to SPM.

On the other hand, the hardware chosen for the fMRI data analysis may depend on the platform already present in the laboratory or the supporting software. Unix[13] was first developed in 1969. The most famous feature of Unix is its so-called multi-user/multi-task functionality. Many users can simultaneously operate a single Unix machine and simultaneously perform many tasks. Linux has inherited many advantages of Unix. Since it can be freely distributed and modified, Linux has attracted the interest of many researchers. On the other hand, Windows is run on personal computers (PCs), which are inexpensive and more user-friendly. In addition, many more software packages are available for Windows other than those for analyzing fMRI data, compared with Unix and Linux. Although Windows, Unix and Linux have many common features regarding personal use, Windows and Linux may be superior to Unix with regard to cost-efficiency, especially considering the prices of applicable software packages and peripheral equipment, including memory and storage devices. This may explain why personal computers are the fastest growing segment of the workstation market. Furthermore, Windows clearly dominates the OS market.

We need various kinds of the machines to analyze simultaneously huge amount of fMRI data. If each machine offers different results of the fMRI data analysis in spite of using the same data and software, it will create problem to be considered in terms of obtaining meaningful and accurate results in human brain function.

The purpose of this study was 1) to examine whether we could analyze fMRI data and obtain identical results on different PCs and 2) to compare the differences and limitations in running SPM99 software to analyze fMRI data among Windows-, Unix- and Linux-based systems.

Materials and Methods

Subjects

Six normal right-handed[14] volunteers (5 males, 27-29 years of age), with no history of psychiatric or neurological illness, participated in the study. All the experimental procedures were in compliance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). The Institutional Ethical Review Board for research involving human subjects approved the study protocol. Informed consent was obtained from the subjects before the study, after the nature of the experimental procedures was explained.

Tasks and fMRI data acquisition

All of the subjects performed the following two tasks; 1) “rest” as a control and 2) grasping with the right hand (“right hand”). During “rest”, the subject was relaxed and a light soft sponge ball, 60 mm in diameter, was kept in weak contact in the right palm. During “right hand”, the subject performed self-paced grasping of the soft ball in the right palm, using all digits. Instructions on when to begin each task were presented in the form of single Chinese characters at the center of the visual field. The visual field for the subjects was adjusted in a mirror before MR scanning. Each subject lay in the supine position in the MR scanner and wore headphones to reduce the noise of the scanner. The room was dark to highlight the visual field. We used appropriate straps to minimize movements of the head, body and arms. After the initial positioning image was obtained, imaging with a T1-weighted sequence was performed to obtain structural MR images of the subject’s brain.

Each subject performed a run that consisted of 98 images (40 axial T2*-weighted slices, repetition time: 4117 ms, slice thickness: 3 mm, echo time: 40 ms, recovery time: 60 ms, flip angle: 90 degrees, field of view: 192 mm, matrix size: 64×64 pixels, voxel size: $3 \times 3 \times 3$ mm). The subject performed 12 periods of approximately 32 s (i.e., 10 whole-brain images/period for the first period and 8 whole-brain images/period for the remaining periods). The run was measured using a gradient echo-type echo planar imaging (EPI) sequence on a 1.5T apparatus (Magnetom Vision, Siemens AG, Erlargen, Germany) with a head coil. For each subject, data from the initial 2 scans within the first period of "rest" were discarded to eliminate transients arising before dynamic equilibrium was achieved.

Data analysis

The fMRI data were realigned to remove movement-related artifacts using SPM99 software (Wellcome Department of Cognitive Neurology, London, U.K., http://fil.ion.ucl.ac.uk/spm), which is affinitive to MATLAB version 5.3/6.1 (The MathWorks, inc., http://www.mathworks.com/) functions and subroutines (with some externally compiled C routines). The anatomic images were spatially normalized using both linear and nonlinear parameters with a human brain atlas system, and the same parameters were used for spatial normalization of the functional images. The fMRI data were then smoothed with a Gaussian filter with a full width at half-maximum of 6 mm. The resultant set of voxel values for each contrast constitutes the SPM of the statistical t SPM (t). These t values constitute the SPM (t), which is transformed to a normal distribution to obtain SPM (Z), which has a threshold at $p < 0.05$ (corrected for multiple comparisons). The statistically significant locations were expressed as coordinates and superimposed on a standard brain atlas[15].

Comparisons of fMRI data analysis by using PC, Unix and Linux machines

We used several PC, Unix and Linux machines to analyze fMRI data. The differences in the central processing unit (CPU), memory, and other specifications are delineated in Table 1. For comparisons, fMRI data from the runs in the 6 subjects (i.e., individual fMRI images of 96 brain volumes) were used. We then identified regions where significantly increased activation during "right hand" relative to "rest" was seen by means of subtraction analysis. To examine the limitation of scans per session during estimations by SPM99 software, we divided fMRI data into subsets of 500 images (i.e., *img, r*img, nr*img and snr*img, see Table 3), upon which pre-statistics had been performed.

Results

The detailed transparent projection of foci in the whole brain activated during "right hand", which were elucidated by analyzing fMRI data using PC, Unix and Linux machines, is shown in Fig. 1. The left primary sensorimotor cortex (S1/M1) and thalamus were activated in all instances. In addition, the supplementary motor area (SMA) and right cerebellum were activated when analyzed by all of the PC and Unix machines. There seemed to be no qualitative differences in the size or location of the activated foci between the machines that were used for analysis.

The quantitative analysis of three-dimensional locations of activated foci is summarized in Table 2. In the S1/M1, the x-, y- and z-coordinates of foci with the highest, second-highest and third-highest T-values for each machine were identical, and did not depend on the kind of machine or differences in the CPU and memory. Similar results were found for the cerebellum and the SMA.

Although a group analysis of fMRI data gave identical results in several PC, Unix and Linux machines, most

Table 1. Specifications of PC, Unix and Linux machines.

machine name (type)	CPU	RAM	virtual memory	hard drive	OS/platform	MATLAB Version
Gateway1 (PC)	Pentium II 400MHz	256MB	off	20GB	Windows98	5.3
Gateway2 (PC)	PentiumIII 600MHz	512MB	1GB	30GB	Windows98 SE	5.3
Compaq1 (PC)	PentiumIII 933MHz	512MB	automatically	30GB	Windows98 SE	5.3
Compaq2 (PC)	PentiumIII 933MHz	512MB	off	30GB	Windows98 SE	6.1
Compaq notebook (PC)	PentiumIII 700MHz	64MB	automatically	12GB	Windows98 SE	5.3
Endeavor (PC)	PentiumIV 1.7GHz	512MB	automatically	80GB	Windows2000 Pro	6.1
Vaio (PC)	PentiumIII 1.0GHz	256MB	automatically	40GB	WindowsXP HE	6.1*
Sun (Unix)	UltraSPARC 400MHz	512MB	1GB	20GB	Solaris 8	5.3
PC-Linux (Linux)	PentiumIII 933MHz	512MB	1GB	30GB	Redhat 7.2	6.1

Abbreviations: PC, personal computer; CPU, central processing unit; RAM, random-access memory; OS, operating system; SE, second edition; Pro, professional; HE, home edition; *, not supported by The MathWorks (http://www.mathworks.com/)

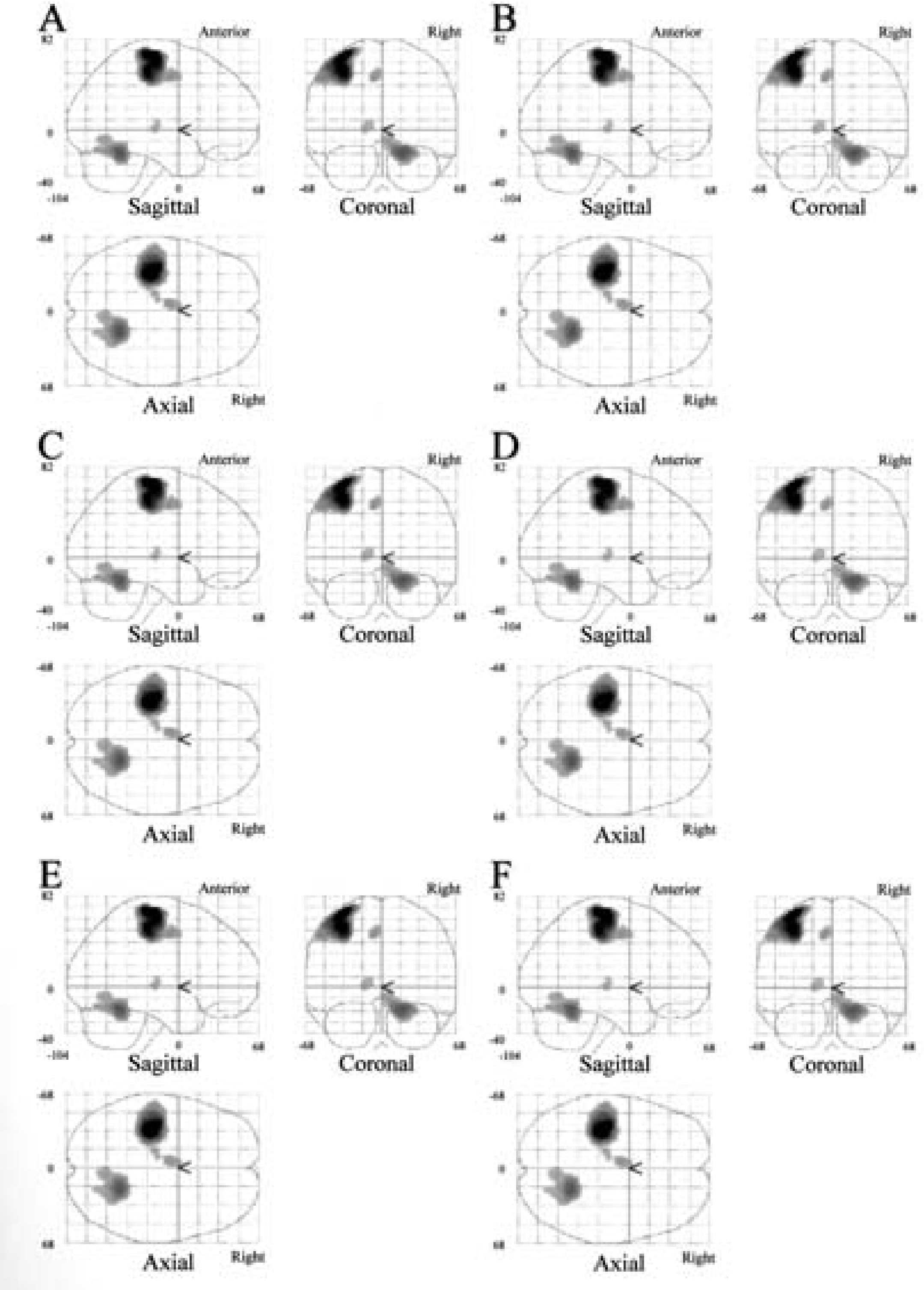

Fig. 1. Group results (n=6) showing significant signal increases associated with grasping by the right hand, which were analyzed using different personal computers/workstation. Regions of significant signal increase ($p < 0.05$ corrected for multiple comparisons) are shown as projections onto a "glass brain" with three-dimensional coordinates according to Talairach and Tournoux (1988). Arrowheads indicate the origin of x-, y- and z-coordinates. A: Gateway1, B: Compaq1, C: Endeavor, D: Vaio, E: Sun, F: PC-Linux. Abbreviations: Sagittal, sagittal view of the brain; Coronal, coronal view of the brain; Axial, axial view of the brain.

Table 2. x-, y-, z-coordinates, T-value and Z-score of the activation foci during grasping by the right hand (“right hand” – “rest”) revealed by analysis with different machines.

Machine name (type)	Activation foci	x	y	z	T-value	Z-Score
Gateway1 (PC)	S1/M1(L)	-34	-24	68	27.18	Inf
		-34	-28	54	21.72	Inf
		-52	-22	48	9.42	Inf
	cerebellum(R)	20	-52	-20	13.81	Inf
		6	-66	-8	7.24	6.99
		20	-72	-18	6.21	6.05
	SMA	-6	-6	48	8.52	Inf
	thalamus	-14	-20	2	6.72	6.52
Compaq1 (PC)	S1/M1(L)	-34	-24	68	27.18	Inf
		-34	-28	54	21.72	Inf
		-52	-22	48	9.42	Inf
	cerebellum(R)	20	-52	-20	13.81	Inf
		6	-66	-8	7.24	6.99
		20	-72	-18	6.21	6.05
	SMA	-6	-6	48	8.52	Inf
	thalamus	-14	-20	2	6.72	6.52
Endeavor (PC)	S1/M1(L)	-34	-24	68	27.18	Inf
		-34	-28	54	21.72	Inf
		-52	-22	48	9.42	Inf
	cerebellum(R)	20	-52	-20	13.81	Inf
		6	-66	-8	7.24	6.99
		20	-72	-18	6.21	6.05
	SMA	-6	-6	48	8.52	Inf
	thalamus	-14	-20	2	6.72	6.52
Vaio (PC)	S1/M1(L)	-34	-24	68	27.18	Inf
		-34	-28	54	21.72	Inf
		-52	-22	48	9.42	Inf
	cerebellum(R)	20	-52	-20	13.81	Inf
		6	-66	-8	7.24	6.99
		20	-72	-18	6.21	6.05
	SMA	-6	-6	48	8.52	Inf
	thalamus	-14	-20	2	6.72	6.52
Sun (Unix)	S1/M1(L)	-34	-24	68	27.18	Inf
		-34	-28	54	21.72	Inf
		-52	-22	48	9.42	Inf
	cerebellum(R)	20	-52	-20	13.81	Inf
		6	-66	-8	7.24	6.99
		20	-72	-18	6.21	6.05
	SMA	-6	-6	48	8.52	Inf
	thalamus	-14	-20	2	6.72	6.52
PC-Linux (Linux)	S1/M1(L)	-34	-24	68	27.18	Inf
		-34	-28	54	21.72	Inf
		-52	-22	48	9.42	Inf
	cerebellum(R)	20	-52	-20	13.81	Inf
		6	-66	-8	7.24	6.99
		20	-72	-18	6.21	6.05
	SMA	-6	-6	48	8.52	Inf
	thalamus	-14	-20	2	6.72	6.52

Several foci with high T-value are shown. Stereotaxic coordinates (in mm) are expressed according to Talairach and Tournoux (1988). Abbreviations: PC, personal computer; S1/M1, primary sensorimotor cortex; SMA, supplementary motor area; R, right hemisphere; L, left hemisphere. Z-score; Inf > 8.0.

Table 3. Limitations of PC, Unix and Linux machines in scans per session on each processing.

	Processing							
	Realignment	Normalization	Smoothing	Estimation				
machine name (type)	3000img	r3000img	nr3000img	snr500img	snr1000img	snr1500img	snr2000img	snr3000img
Gateway1 (PC)	○	○	○	○	○	×	×	×
Gateway2 (PC)	○	○	○	○	○	×	×	×
Compaq1 (PC)	○	○	○	○	○	×	×	×
Compaq2 (PC)	○	○	○	○	○	×	×	×
Compaq notebook (PC)	○	○	○	○	○	×	×	×
Endeavor (PC)	○	○	○	○	○	○	○	○
Vaio (PC)	○	○	○	○	○	○	○	○
Sun (Unix)	○	○	○	○	○	○	○	○
PC-Linux (Linux)	○	○	○	○	○	○	○	○

snr*img stands for a number of scans per session, upon which pre-statistics (s: smoothed, n: normalized, r: realigned) have been performed.
○: complete in processing; ×: incomplete in processing.

PC machines were quite limited in estimating by SPM99 (Table 3). Three thousand images could be handled in each realignment, normalization and smoothing process under any condition. However, during estimation, some PC machines froze at the same point in processing with error messages: i.e., when the number of scans per session with pre-statistics exceeded 1000 images, the estimation was incomplete for some PC machines. In contrast, the Unix and Linux machines completed the estimation for up to 3000 images.

Discussion

The activated regions with significant BOLD-signal increases associated with grasping by the right hand (“right hand”-”rest”) in our study were consistent with those in a previous study[16]. Due to the nature of this study, we do not address the physiological meaning of the activated regions.

Windows dominates the OS market. In fact, there seems to be a strategic shift among PC developers, who are currently marketing a version of Windows. Although Unix and Linux concede the major role in the PC market to Windows, it is a practical entry to the workstation and supercomputer. However, most laboratories contain many PCs equipped with the Windows or Mac OS, but not Unix or Linux. On the other hand, many software packages have been developed to investigate human brain function. The choice of which software package to use would depend on the purposes, interests and goals of each researcher in each laboratory. Software packages require the choice of a basic language (e.g., C, C++, MATLAB) and OS/platform (e.g., Windows 98, Macintosh OS, Unix, Linux). Thus, the OS/platform chosen for fMRI data analysis may depend not only on the platform present in the laboratory, but also on the programming expertise available. Machines that are equipped with Unix and Linux as the OS and C as the basic language are generally used to analyze the considerable amount of fMRI data.

The OS provides an application-programming interface to allow software to run smoothly and to control hardware. Practically, the OS can be classified into 3 types; client OS (e.g., Windows 95/98, Macintosh OS), network OS (e.g., Windows NT), and multi-user OS (e.g., Unix). Control of memory is one of the most important functions of the OS, and the concept of virtual memory has been developed. Virtual memory, which is different from physical memory, has various functions in addition to behaving like a computer with a huge amount of memory.

In this study, we used 7 PC machines and Unix and Linux machines with different specifications regarding the CPU, memory, and hard drive. The speed of calculation depends on the CPU, whereas the amount of memory and the size of the hard drive define the amount of data that can be processed at any one time. The amount of fMRI data in our study was quite large; approximately 350 bytes (B) per image for the heading part, and 980 KB per image for the data part. This equates to approximately 100 MB/100snr*imgs. Therefore, it is conceivable that a machine equipped with a small amount of random-access memory (RAM) and/or insufficient virtual memory could freeze during processing. Nonetheless, pre-statistics (i.e., realignment, normalization and smoothing) could be accomplished using the *Compaq notebook* computer, which has only 64 MB of RAM. This indicates that the virtual memory set-up may compensate for the shortage of RAM in this machine. On the other hand, there were no problems with the Gateway1 computer, which was equipped with 256 MB of RAM and no virtual memory. Thus, it appears that 256 MB of RAM is adequate for performing pre-statistics.

However, 256 MB of RAM may be insufficient for analyzing fMRI data encompassing the whole brain. It is plausible that some contrivances are used in the analysis with SPM99; each voxel value in the three-dimensional coordinate space of the whole brain may not be allocated a separate memory address as an array element. Rather, only voxel values for ongoing calculation (i.e., a few slices of the partial brain data) may be allocated a memory address. When the calculation is complete, the memory address is erased and new voxel data are allocated a memory address.

Some PC machines stopped processing during estimation after finishing pre-statistics. This can be attributed to the insufficient memory in such PC machines. Indeed, MATLAB showed an error message, “insufficient memory space”. However, the PC machines had the same amount of memory as the Unix and Linux machines if virtual memory was included. Both the Unix and Linux machines would have stopped processing at the same level of estimation as PCs if the amount of memory was the only concern, and PCs equipped with different amounts of memory would give different results. Therefore, the amount of memory alone does not seem to account for this freezing. Although the whole-brain data from each subject are subjected to pre-statistics by SPM99 on a by-subject basis, the whole-brain volume data from all of the subjects are subjected to estimation simultaneously. This requires an ability to process a huge data file. Windows machines can deal with a maximum size of 2 GB or 4 GB as a single file, with the exception of Windows 2000/NT/XP, due to the file system. The maximum size in our PC machines was limited to 4 GB, since the file allocation table (FAT) was set at 32 in Windows 98 machines. While estimating data using SPM99 in the present study, it seems that the size of a single file in the data exceeded this limit, which forced the machine to stop functioning. Indeed, only 2 PCs (i.e., Endeavor and Vaio) completed the estimation.

Other than this limitation in the size of the data file, there were no significant differences in efficiency among the Windows, Unix and Linux machines. Therefore, the stability of the system is thought to be the most important aspect for comparison. Despite the recent progress in OS design, where virtual memory has been used to compensate for a shortage of actual memory, programs that use large amounts of virtual memory and exchange huge data files between the CPU and hard drive may predispose the machine to freezing. Thus, the stability of the machine becomes the most important factor in calculations where large amounts of data are involved and a long computation time is expected. In our study, we did not encounter any problems in running SPM99 software on PC machines for performing pre-statistics (i.e., realignment, normalization and smoothing) on fMRI data and for estimating a certain amount of fMRI data, upon which pre-statistics had already been performed. Nonetheless, if we have to analyze a huge amount of fMRI data, Windows 2000/XP, Unix, and Linux machines are essential for solving problems in which the experimental paradigms are complicated, as in an fMRI study.

Acknowledgements

This research was supported by Grants-in-Aid (10307052, 09470467, and 143706191) from the Japanese Ministry of Education, Science, Sports and Culture.

References

1. Ogawa S, Lee TM, Kay AR, et al. Brain magnetic resonance imaging with contrast dependent on blood oxygenation. Proc Natl Acad Sci USA 1990;87(24):9868-72.
2. Ogawa S, Lee TM. Magnetic resonance imaging of blood vessels at high fields: *in vivo* and *in vitro* measurements and image simulation. Magn Reson Med 1990;16(1):9-18.
3. Turner R, Le Bihan D, Moonen CT, et al. Echo-planar time course MRI of cat brain oxygenation changes. Magn Reson Med 1991;22(1):159-66.
4. Frahm J, Merboldt KD, Hanicke W, et al. Brain or vein—oxygenation or flow? On signal physiology in functional MRI of human brain activation. NMR Biomed 1994;7(1-2):45-53.
5. Hathout GM, Gambhir SS, Gopi RK, et al. A quantitative physiologic model of blood oxygenation for functional magnetic resonance imaging. Invest Radiol 1995;30(11):669-82.
6. Rao SM, Binder JR, Bandettini PA, et al. Functional magnetic resonance imaging of complex human movements. Neurology 1993;43:2311-18.
7. Corfield DR, Murphy K, Josephs O, et al. Cortical and subcortical control of tongue movement in humans: a functional neuroimaging study using fMRI. J Appl Physiol 1999;86:1468-77.
8. Shinagawa H, Ono T, Ishiwata Y, et al. Hemispheric dominance of tongue control depends on the chewing-side preference. J Dent Res 2003;82:278-83.
9. Millen SJ, Haughton VM, Yetkin Z. Functional magnetic resonance imaging of the central auditory pathway following

speech and pure-tone stimuli. Laryngoscope 1995;5:1305-10.
10. Miki A, Liu GT, Goldsmith ZG, et al. Effects of check size on visual cortex activation studied by functional magnetic resonance imaging. Ophthalmic Res 2001;33:180-4.
11. O'Doherty J, Rolls ET, Francis S, et al. Representation of pleasant and aversive taste in the human. J Neurophysiol 2001;85:1315-21.
12. Gold S, Christian B, Arndt S, et al. Functional MRI statistical software packages: a comparative analysis. Hum Brain Mapp 1998;6:73-84.
13. Ni DC. Enumeration and traceability tools for UNIXTM and WINDOWSTM environments. J Systems Software 1997;39:15-25.
14. Oldfield RC. The assessment and analysis of handedness: the Edinburgh Inventory. Neuropsychologia 1971;9:97-113.
15. Talairach J, Tournoux P. Co-Planar Stereotaxic Atlas of the Human Brain. New York:Thieme; 1988.
16. Ehrsson HH, Fagergren A, Jonsson T, et al. Cortical activity in precision- versus power-grip tasks: an fMRI study. J Neurophysiol 2000;83:528-36.