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神作憲司. 発達と脳内機構. *第103回日本小児精神神経学会研究大会.* 2010年6月; 東京

B. 知的財産権の出願・登録状況

1. 特許取得

外山滋、神作憲司、高野弘二、池上史郎. 脳波測定用電極、脳波測定用電極付きキャップ及び脳波測定装置. (特願 2009-257366). 出願日 2009.11.10. (特願 2010-119930). 出願日 2010.5.25.

2. 実用新案登録

なし

3. その他

なし

厚生労働科学研究費補助金（活動領域拡張医療機器開発研究事業）
分担研究報告書
ブレイン―マシン・インターフェイス（BMI）による障害者自立支援機器の開発に関する研究

分担研究課題名　ロボットスーツHALの障害者自立支援機器への展開に関する研究

研究分担者　山海　嘉之　筑波大学大学院システム情報工学研究科教授

研究要旨

本研究は、活動領域拡張医療機器開発事業として、ブレイン―マシン・インターフェイス（BMI）による障害者自立支援機器の開発に関して、研究を推進するものである。BMIに関しては、非侵襲型のインタフェースを用いることとし、また、障害者自立支援機器として、これまで研究開発を進めてきたロボットスーツHALを改良・活用する。本年度は、従来装置を改良することによって、下肢用試験システムの開発推進、ならびに、上肢用試験システム、把持動作支援用のハンド・フィンガー部を準備し、実験を行った。

A. 研究目的

本研究では、活動領域拡張医療機器開発事業として、ブレイン―マシン・インターフェイス（BMI）による障害者自立支援機器の開発に関して、研究を推進することを目的としている。

従来装置を改良することによって、下肢用試験システムの開発推進、ならびに、上肢用試験システム、把持動作支援用のハンド・フィンガー部を準備し、基礎的実験を行う。

B. 研究方法

現状のBMI技術による分解能を検討すると、侵襲型であっても非侵襲型であっても高い分解能を期待する事は現時点では困難であるため、検討の結果、本研究では非侵襲型の適用が当面は妥当であると判断し、これを想定して研究を進めている。また、運動機能障害者の自立支援機器として、これまで研究開発を進めてきたロボットスーツHALを改良・活用することで研究推進の効率化をはかり、改良型試験装置の製作と基礎実験を行う。

（倫理面への配慮）

人支援技術の研究開発の推進には、被験者に対する適切な対応が求められるため、当該研究では、厚生労働省の臨床研究に関する倫理指針を遵守した。

C. 研究結果

研究開発方針に従って、従来から研究開発を進めてきた下肢用試験システムの開発推進、ならびに、上肢用試験システム、把持動作支援用のハンド・フィンガー部を当該研究開発推進のために改良を行い（機構的／電子的／制御論的機能の拡充)、動作試験等の実験を継続している。

従来より開発を進めてきた装着型サイバニックハンド・フィンガーに改良を加え（図1)、さらなる小型軽量化や制御精度向上を目指し、現在改良試作および動作検証を進めている。準備を進めている上肢と接合すべく改良を加えている。

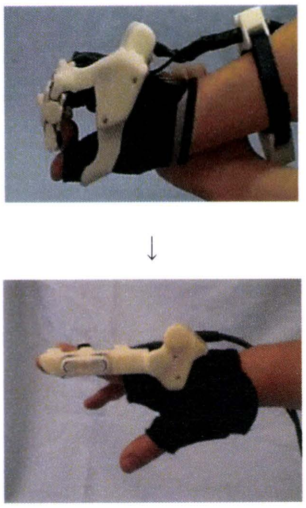

図1　装着型サイバニックハンド・フィンガー（改良版）

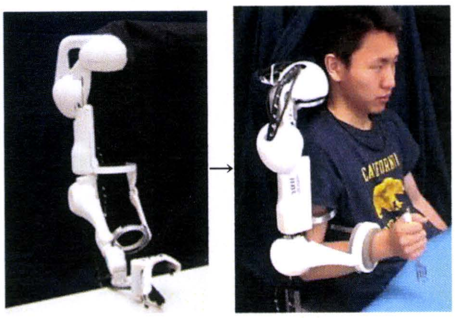

図2　上肢用 HAL

また、従来より開発を進めてきた上肢用 HAL についても図 2 に示すような改良を加え、動作検証を実施中である。

さらに、単関節下肢用 HAL のインタフェース部に対して、BMI との連動が可能となるよう、機構的／電子的／制御論的機能の改良を行っている。更に、BMI に関しても可能な範囲で試行を実施した。図 4 に示すような試作品を制作した。システム全体を組み上げてゆく過程で、要素技術が機能していることを確認するために、簡単なシステムを構成し、脳活動パターンの信号を用いて基礎実験を試みている。

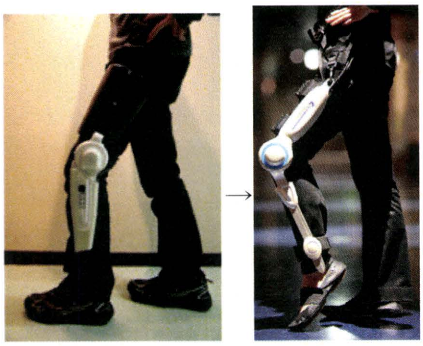

図3　単関節下肢用 HAL（インタフェース改良版）

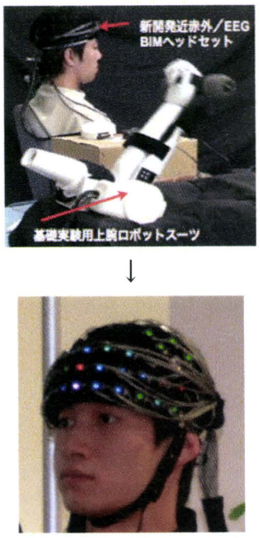

図4　新開発 BMI ヘッドセット

D. 考察

各要素の技術的な改良を行なうことができた。システム全体については、現在、全体の動作検証を進めている。別途インタフェースユニットを構成することも検討する。

E. 結論

当該研究推進のため、機構的／電子的／制御論的機能を自律システムとして適用できるよう要素技術の研究開発を進めることができた。

F. 健康危険情報

該当なし

G. 研究発表

（これまでの関連研究の成果を含む）

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３． 著書

1) ロボットスーツ「HAL®」開発・実用化への舞台裏, 中央公論, pp. 78-85, 2011 年 3 月号

Ｈ．知的財産権の出願・登録状況
（これまでの関連研究の成果を含む）

1.　関連する特許取得（平成２２年度　出願）

1) 発明の名称：装着式動作補助装置のキャリブレーション装置, 及びキャリブレーション用プログラム

出願人：筑波大学

出願番号：特願 2010−181601

2) 発明の名称：診断装置

出願人：筑波大学

出願番号：特願 2010−198554

2　実用新案登録

該当なし。

III.　研究成果の刊行に関する一覧表

研究成果の刊行に関する一覧表

書籍

著者氏名	論文タイトル名	書籍全体の編集者名	書　籍　名	出版社名	出版地	出版年	ページ
Kansaku, K	Brain-Machine Interfaces for environmental control and communication.	Kansaku, K., Cohen, L.G.	Systems Neuroscience and Rehabilitation.	Springer Verlag	Tokyo		in press
Kansaku, K	The Intelligent Environment: Brain-Machine Interfaces for Environmental Control	Ferguson-Pell, M., Stefanov, D	Smart Houses: Advanced Technology for Living Independently	Springer Verlag	Berlin		in press

雑誌

発表者氏名	論文タイトル名	発表誌名	巻号	ページ	出版年
Ikegami, S., Takano, K., Saeki, N., Kansaku, K.	Operation of a P300-based brain-computer interface by individuals with cervical spinal cord injury	Clinical Neurophysiology			in press
Kansaku, K., Hata, N., Takano, K	My thoughts through a robot's eyes: an augmented reality-brain-machine interface	Neuroscience Research	66(2)	219-222	2010
神作憲司	発達と脳内機構	小児の精神と神経	50(4)	369-371	2010
神作憲司	脳波による家電操作：シリーズ・リハを支えるテクノロジー最前線	Journal of Clinical Rehabilitation	19(11)	1012-1016	2010
神作憲司	ブレイン・リーディング	Clinical Neuroscience	28(9)	1069-1071	2010
池上史郎、神作憲司	ブレイン-マシン・インターフェイス（BMI）の今後の展開	作業療法ジャーナル	44(4)	292-297	2010
神作憲司	脳からの信号で家電を操作	日本肢体不自由児協会報「はげみ」	335	13-18	2010

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Shiori Oshima, Yoshiyuki Sankai	Development of Optical Sensing System for Noninvasive and Dynamic Monitoring of Thrombogenic Process	ASAIO Journal	56(5)	460-467	2010
Kenta Suzuki, Gouji Mito, Hiroaki Kawamoto, Yasuhisa Hasegawa,Yoshiyuki Sankai	Intention-Based Walking Support for Paraplegia Patient with Robot SuitHAL	Climbing and Walking Robots		383-408	2010
佐藤帆紡, 川畑共良, 田中文英, 山海嘉之	ロボットスーツHALによる移乗介助動作の支援	日本機械学会誌(C編)	76(762)	227-235	2010
新宮正弘,江口清, 山海嘉之	バイオフィードバックを用いたポリオ経験者の筋神経系制御能力の改善とロボットスーツ HAL による麻痺肢動作支援	日本機械学会誌(C編)	76(772)	3630-3639	2010

IV.　研究成果の刊行物・別刷

ARTICLE IN PRESS

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Operation of a P300-based brain–computer interface by individuals with cervical spinal cord injury

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ABSTRACT

Objective: This study evaluates the efficacy of a P300-based brain–computer interface (BCI) with green/blue flicker matrices for individuals with cervical spinal cord injury (SCI).

Methods: Ten individuals with cervical SCI (age 26–53, all male) and 10 age- and sex-matched able-bodied controls (age 27–52, all male) with no prior BCI experience were asked to input hiragana (Japanese alphabet) characters using the P300 BCI with two distinct types of visual stimuli, white/gray and green/blue, in an 8×10 flicker matrix. Both online and offline performance were evaluated.

Results: The mean online accuracy of the SCI subjects was 88.0% for the white/gray and 90.7% for the green/blue flicker matrices. The accuracy of the control subjects was 77.3% and 86.0% for the white/gray and green/blue, respectively. There was a significant difference in online accuracy between the two types of flicker matrix. SCI subjects performed with greater accuracy than controls, but the main effect was not significant.

Conclusions: Individuals with cervical SCI successfully controlled the P300 BCI, and the green/blue flicker matrices were associated with significantly higher accuracy than the white/gray matrices.

Significance: The P300 BCI with the green/blue flicker matrices is effective for use not only in able-bodied subjects, but also in individuals with cervical SCI.

1. Introduction

Brain–computer interfaces (BCI) or Brain–machine interfaces (BMI) are devices that use neurophysiological brain signals to control external computers or machines (Wolpaw et al., 2002; Daly and Wolpaw, 2008; Kansaku, in press). One approach to using these devices, invasive BCI, relies on electrical signals recorded directly from the cortical surface (electrocorticograph; ECoG) or a single neuron (unit recording) (Kennedy et al., 2000; Leuthardt et al., 2004; Hochberg et al., 2006). The other approach, non-invasive BCI, uses electrical signals from the brain in the absence of surgery. The primary approach for non-invasive BCI is electroencephalography (EEG), where neurophysiological signals are recorded from an array of scalp electrodes.

Several types of electrical brain activity have been proposed for controlling EEG-based BCI. These include sensorimotor rhythm, slow cortical potential, steady state visual evoked potential, and P300 event-related potential. If the chosen communication system results in more than 70% correct responses, it has potential for practical use as a BCI system in people with disabilities (Sellers et al., 2006; Kübler and Birbaumer, 2008; Nijboer et al., 2008). Some BCI systems have already reached this level. Thus, BCI systems based on P300 signals were tested in patients with amyotrophic lateral sclerosis (ALS) and other diseases either in a laboratory setting (Piccione et al., 2006; Sellers and Donchin, 2006; Hoffmann et al., 2008) or the patient's home (Nijboer et al., 2008). The majority of subjects used in these studies were patients with ALS, and no studies have examined age- and sex-matched controls for comparison.

Our research group recently developed a BCI system for environmental control and communication (Komatsu et al., 2008; Kansaku et al., 2010), in which we applied several flicker panels that were modified from the "P300 speller" (Donchin et al., 2000), which uses P300-like evoked signals. We previously reported that a male volunteer quadriplegic SCI (C3/C4) patient successfully controlled our device without significant training (Komatsu et al., 2008). However, we sought to develop better visual stimuli because the white/gray flicker stimuli used could

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possibly induce discomfort or seizures, particularly in subjects with a history of epilepsy. Parra et al. evaluated the safety of chromatic combinations for those with photosensitive epilepsy (Parra et al., 2007). Five single-color stimuli (white, blue, red, yellow, and green) and four alternating-color stimuli (blue/red, red/green, green/blue, and blue/yellow with equal luminance) of four frequencies (10, 15, 20, and 30 Hz) were used as the visual stimuli. Under white stimulation, flickering stimuli with higher frequencies, especially those greater than 20 Hz, have been found to be potentially provocative. Under the alternating-color stimulation condition, as suggested by the Pokemon incidence, the 15-Hz blue/red flicker was the most provocative. It is noteworthy that the green/blue chromatic flicker emerged as the safest and evoked the lowest rates of EEG spikes. Accordingly, we used the green/blue chromatic combination for the visual stimuli used to elicit visually evoked responses (Takano et al., 2009b). We prepared a white/gray flicker matrix for the luminance flicker, a green/blue isoluminance flicker matrix for the chromatic flicker, and a green/blue luminance flicker for the luminance and chromatic flicker. We applied the experiments to the able-bodied subjects, and showed that accuracy rates were significantly higher in response to the luminance chromatic flicker condition than in response to the luminance or chromatic flicker condition. We also found that the green/blue luminance flicker matrices significantly improved subjective feelings of comfort in able-bodied subjects compared to the white/gray flicker matrices (Takano et al., 2009a).

This study focuses on the efficacy of the P300 BCI in individuals with chronic cervical SCI, who are potential users of the system (Daly and Wolpaw, 2008). We compared individuals with chronic cervical SCI and age- and sex-matched able-bodied controls. Subjects had no prior experience with the P300 BCI and were required to input hiragana (Japanese alphabet) characters using our P300 BCI system using either white/gray or green/blue luminance flicker matrices. We show that the P300 BCI with the green/blue flicker matrix is effective not only for use in able-bodied subjects, but also in individuals with cervical SCI.

2. Materials and methods

2.1. Subjects

Ten individuals with chronic cervical SCI (age 26–53, mean 41.9, all male) with no prior experience with BCI devices were recruited as participants. The mean time since SCI was 18.2 years (range, 5.5–29.2 years). Five individuals were diagnosed with complete tetraplegia according to the American Spinal Injury Association (ASIA) impairment scale (Maynard et al., 1997) (summarized in Table 1). All of the SCI patients had severe upper extremity dysfunction and needed the help of caregivers to use appliances for emailing and other tasks, and most needed Alternative Augmentative Communication (AAC) devices (e.g., mouth stick). All SCI subjects were outpatients and visited the laboratory in wheelchairs. In addition, 10 age- and sex-matched able-bodied controls (age 27–52, mean 42.1, all male) with no prior experience with BCI devices were recruited. This study was approved by the Institutional Review Board, and all subjects provided written informed consent according to institutional guidelines.

3. Experimental procedure

We modified the so-called P300 speller (Farwell and Donchin, 1988). The P300 speller uses the P300 paradigm and involves the presentation of a selection of icons arranged in a matrix. According to this protocol, the participant focuses on one icon in the matrix as the target, and each row/column, or a single icon of the matrix is then intensified in a random sequence. The target stimuli are presented as rare stimuli (i.e., the oddball paradigm). We elicited P300 responses to the target stimuli and then extracted and classified these responses with respect to the target.

All subjects sat approximately 100 cm away from a liquid crystal display that displayed a flicker matrix and input window (Fig. 1). SCI subjects used their own wheel chair, and control subjects sat in a desk chair. We prepared an 8×10 hiragana matrix for the P300 speller, modified from a 6×6 matrix using the English alphabet (Takano et al., 2009b). We used two types of intensification/rest flicker conditions, white/gray and green/blue. Luminance was measured using a chromatic meter (CS-200, Konica Minolta Sensing Inc., Osaka, Japan), and was 20 cd/cm(white)/6.5 cd/cm(gray), and 20 cd/cm(green)/6.5 cd/cm(blue), for each condition. The duration of intensification (green or white) was 100 ms, and that of rest (blue or gray) was 75 ms (Blankertz et al., 2006; Sellers et al., 2006). Each row and column of the matrix was intensified once per sequence in random order and, according to the P300 paradigm, the target stimuli were presented as rare stimuli (i.e., the oddball paradigm). One complete cycle of eight row and ten column intensifications constituted a sequence. Online performance was evaluated, and each letter was selected in a series of 10 sequences (180 intensifications for each hiragana character).

We first collected EEG data to derive feature vectors for the subsequent test session. All subjects were instructed to attend to six successive letters of the matrix under each condition (training session). In the test session, using the feature vectors, all subjects were required to input 15 letters from the 8×10 hiragana matrix under each flicker condition. The order of the experimental conditions (white/gray or green/blue flicker matrix) was counterbalanced between subjects.

3.1. EEG recording and analysis

Eight-channel (Fz, Cz, Pz, P3, P4, Oz, PO7, and PO8) EEG data were recorded with a g-Tec cap and g.USBamp acquisition system (Guger Technologies OEG, Graz, Austria) (Krusienski et al., 2008;

Table 1
Summary of spinal cord injury subjects.

	Age	Sex	Level of SCI at injury	Time since injury (years)	ASIA impairment Scale
SCI	37	M	C3/4	16.3	Incomplete
	45	M	C2/3	5.5	Complete
	43	M	C5/6	25.3	Complete
	40	M	C4/5	15.9	Incomplete
	42	M	C4/5	10.4	Complete
	37	M	C3/4	20.5	Incomplete
	48	M	C4/5	27.1	Complete
	48	M	C5/6	21.8	Incomplete
	26	M	C4/5	9.9	Complete
	53	M	C5/6	29.2	Incomplete
Mean	41.9			18.2	

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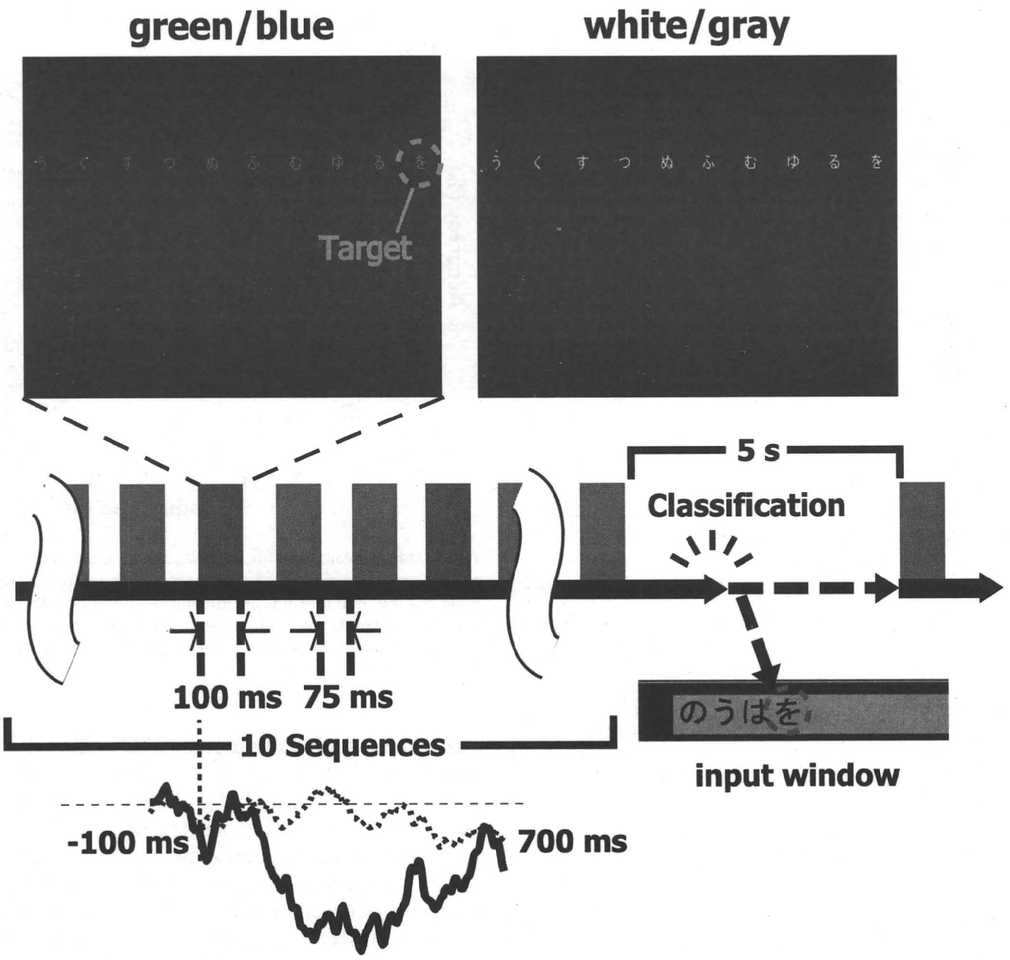

Fig. 1. Task timing for hiragana spelling. Two types of matrix were presented (white/gray and green/blue). The stimulus onset asynchrony was 175 ms, consisting of 100 ms intensification and 75 ms rest. EEG data were collected and used for classification over 10 sequences (180 intensifications). Averaged ERP data (Pz) of the SCI group for the green/blue condition are shown in red (target: thick line, non-target: dotted line).

Takano et al., 2009b). EEG signals were band-pass filtered (0.1–50 Hz), digitized at 256 Hz, and stored. All channels were referenced to Fpz and grounded to AFz. Recorded EEG data were downsampled to 21 Hz for analysis. A total of 800 ms of EEG data were segmented according to the timing of flash onset. The first 100 ms, occurring just prior to flash onset, was used for baseline correction, and the remaining 700 ms was used for classification. In the training session, feature vectors were derived for each condition (white/gray and green/blue). During the test session, using these feature vectors, target and non-target characters were discriminated using Fisher's linear discriminant analysis. The result of this classification, as the maximum of the summed scores for the each row and column, was used to determine the icon to which the subjects were attending. The intersection of the calculated row and column was regarded as the target.

During online performance, the percentage of characters entered correctly was defined as the classification accuracy and was also translated into bit rate (Wolpaw et al., 2002). Correlations between SCI subjects' accuracy and their demographic characteristics (age, time since injury, ASIA impairment scale score) were evaluated using Spearman's rank correlation coefficient. The effects of patient group (SCI vs. control) and type of flicker matrix (white/gray vs. green/blue) on online accuracy were examined using two-way repeated-measure analysis of valiance (ANOVA).

For offline analysis, the accuracy for each sequence was calculated. The effects of subject group (SCI vs. control), type of flicker matrix (white/gray vs. green/blue), and sequence on accuracy in each sequence were evaluated by three-way repeated-measure ANOVA followed by post hoc paired *t*-tests with Bonferroni correction.

4. Results

4.1. Online performance

All subjects completed the 15-letter spelling task in both the white/gray and green/blue conditions. The mean online accuracy of all subjects was 82.7% for the white/gray condition and 88.3% for the green/blue condition. Under the white/gray condition, the mean accuracy was 77.3% for the control group and 88.0% for the SCI group. Under the green/blue condition, the mean accuracy was 86.0% and 90.7% for control and SCI groups, respectively (Fig. 2). For the SCI group, the mean bit rates (Wolpaw et al., 2002) were 9.8 bit/min and 10.2 bit/min under the white/gray and green/blue conditions, respectively (Table 2). Note that the time interval between character selections was not included for the bit rate calculation. The mean bit rates for controls were 8.4 bit/min and 9.6 bit/min for the white/gray and green/blue conditions, respectively. No significant correlations were observed between the accuracy or bit rate of SCI subjects and demographic characteristics (age, time since injury, ASIA impairment scale score; Spearman's rank correlation coefficient, $p > 0.05$).

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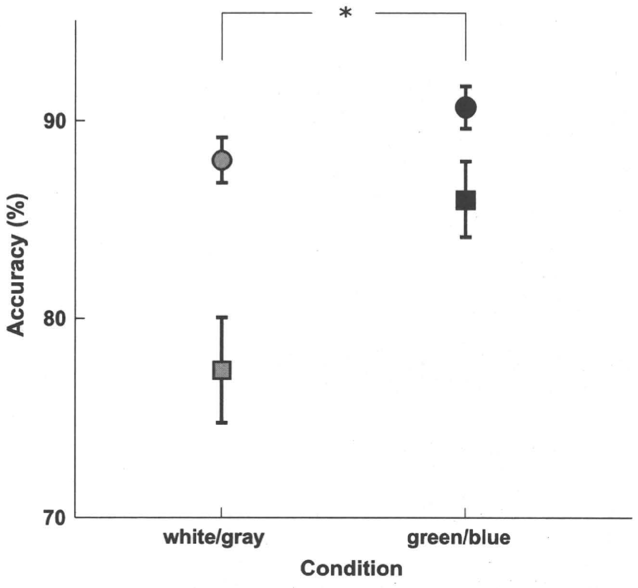

Fig. 2. Online accuracy of subject groups (SCI and controls) for each condition (white/gray and green/blue). Squares, control group; circles, SCI group. Error bars indicate S.E.M.

Table 2
Offline accuracy, bit rate and letter/min during the tenth, eighth, and fifth sequences in SCI subjects.

Sequence (times)	White/gray		Green/blue	
	Accuracy (%)	bit/min	Accuracy (%)	bit/min
10	88.0	9.8	90.7	10.2
8	80.4	10.9	90.4	12.8
5	77.2	16.2	81.7	17.5

We used a two-way repeated-measure ANOVA to examine the effects of group (SCI vs. control) and of condition (white/gray vs. green/blue) on online accuracy. ANOVA revealed a main effect of flicker matrix condition ($F(1,9) = 5.2$, $p < 0.05$). A trend toward greater accuracy in the SCI group compared to controls was observed; however, no main effect of group ($F(1,9) = 1.2$, $p = 0.30$) and no significant interaction ($F(1,9) = 0.61$, $p = 0.45$) was found. These results did not basically change if bit rate was substituted for accuracy.

4.2. Offline evaluation

Fig. 3 shows the results of the offline analysis of subject groups for each condition. We conducted a three-way repeated-measure ANOVA with group (SCI vs. controls), condition (white/gray vs. green/blue), and sequence number (1–10) as factors. Main effects of condition ($F(1,9) = 9.4$, $p < 0.05$) and sequence ($F(9,81) = 93.2$, $p < 0.001$) were significant, but no main effect of group ($F(1,9) = 1.9$, $p = 0.20$) and no significant interaction ($F(9,81) = 0.89$, $p = 0.54$) was found. Thus, the P300 BCI with the green/blue flicker matrix is effective not only in able-bodied subjects but also in individuals with cervical SCI. Accuracy in the first through seventh sequences was significantly lower than that in the tenth sequence, as revealed by post hoc testing ($p < 0.05$, Bonferroni correction).

In the SCI group, the mean online bit rate was 9.8 bit/min and 10.2 bit/min for the white/gray and green/blue conditions, respectively, as calculated from the tenth sequence accuracy (Table 2). In the fifth sequence, the mean accuracy of the SCI group exceeded 70% under both conditions (77.2% for white/gray, 81.7% for green/blue), and the mean bit rate was 16.2 bit/min and 17.5 bit/min for the white/gray and green/blue conditions, respectively (Table 2). In the fifth sequence, the bit rate was significantly higher than in the tenth sequence, but accuracy was significantly lower under both conditions (paired *t*-test, $p < 0.05$). By contrast, in the eighth sequence, accuracy was not significantly different from that in the tenth sequence (80.4% for white/gray, 90.4% for green/blue), and the bit rate was 10.9 bit/min and 12.8 bit/min for white/gray and green/blue, respectively. This bit rate was significantly greater than that in the tenth sequence for green/blue (paired *t*-test, $p < 0.001$), but not for white/gray (paired *t*-test, $p > 0.05$). Thus, the green/blue flicker matrix was more effective than the white/gray flicker matrix by the eighth sequence.

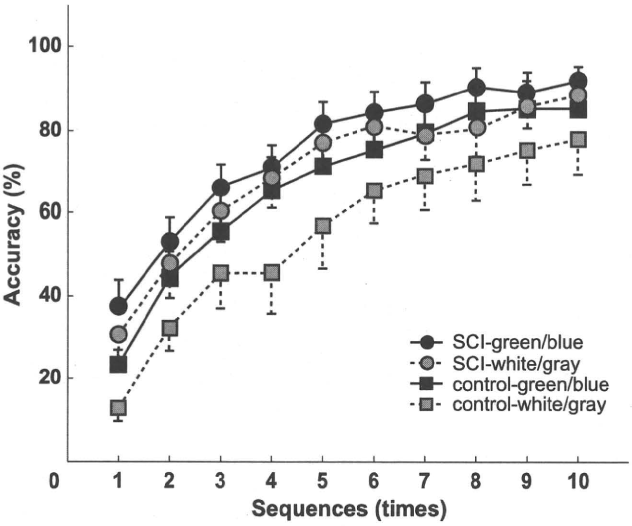

Fig. 3. Offline evaluation for each sequence. Mean accuracy of the control group and SCI group are plotted using squares and circles; the dotted line indicates white/gray, and the solid line indicate green/blue conditions. Accuracy in the first through seventh sequences was significantly lower than that in the tenth sequence, as revealed by post hoc testing ($p < 0.05$, Bonferroni correction). Error bars indicate S.E.M.

5. Discussion

We investigated the accuracy of P300-based BCI performance in individuals with chronic cervical SCI using white/gray and green/blue flicker matrices. SCI patients successfully controlled our BCI system without significant training, and the green/blue flicker matrix provided higher accuracy than the white/gray matrix.

5.1. Effect of the color combination in P300 BCI

A number of studies have attempted to increase P300 BCI performance accuracy, primarily by examining classification methods (Donchin et al., 2000; Kaper et al., 2004; Krusienski et al., 2006; Bashashati et al., 2007; Hoffmann et al., 2008). Other studies have examined modifying matrix size and inter-stimulus intervals (Sellers et al., 2006), type of flash (Guger et al., 2009; Townsend et al., 2010) and background colors (Salvaris and Sepulveda, 2009). We recently reported that a green/blue luminance and chromatic flicker matrix provided higher accuracy than a white/gray luminance flicker matrix and a green/blue isoluminance flicker matrix (Takano et al., 2009b). In the present study, the mean accuracy among both able-bodied and cervical SCI subjects was significantly higher under the green/blue condition than under the white/gray

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condition. No accuracy difference between SCI and able-bodied groups was found.

Online performance of the SCI group reached 90% accuracy and a bit rate of 10.2 bit/min (1.9 letter/min) under the green/blue condition, comparable to previous reports studying disabled subjects (Piccione et al., 2006; Sellers and Donchin, 2006; Hoffmann et al., 2008; Nijboer et al., 2008). This performance is thought to be sufficient for satisfactory use of a BCI, which requires greater than 70% accuracy (Sellers et al., 2006; Kübler and Birbaumer, 2008; Nijboer et al., 2008). Offline analysis showed that number of sequences can be reduced from 10 to 8 while preserving accuracy and significantly increasing the bit rate. This effect was not apparent under the white/gray condition. Thus, the green/blue flicker matrix was more effective for fast communication.

5.2. BCI performance in SCI subjects

P300-based BCI has been examined in SCI subjects in two previous reports of one cervical SCI patient each (Piccione et al., 2006; Hoffmann et al., 2008). One patient controlled a four-choice P300 BCI with an online accuracy of 75.7% (Piccione et al., 2006), and the other controlled a six-choice P300 BCI with an offline accuracy of 100% (Hoffmann et al., 2008). The main BCI method used with SCI subjects is sensorimotor rhythm (SMR) for binary choice (Pfurtscheller et al., 2000; Krausz et al., 2003; McFarland et al., 2005; Kauhanen et al., 2007; Kübler and Birbaumer, 2008). Kauhanen et al. (2007) reported that the mean online accuracy for binary-choice SMR BCI with five cervical SCI subjects was 48%.

Although the brain remains intact in SCI subjects, the deafferentation of sensory input that occurs after SCI can result in brain reorganization and altered scalp EEG activity compared with able-bodied controls (Green et al., 1998; Tran et al., 2004; Herbert et al., 2007). Accordingly, SMR BCI, which uses beta or mu waves from sensory motor areas, would be more affected by this reorganization. Indeed, Kauhanen et al. (2007) reported that the binary-choice SMR BCI performance of five cervical SCI subjects was worse than that of able-bodied subjects (not matched for age and sex). In the present study, individuals with cervical SCI controlled the P300 BCI with similar accuracy to able-bodied individuals. Although the data are limited, the P300 BCI may be easier for SCI subjects to use.

5.3. Toward clinical applications

For practical use of the P300 BCI, the system has to be accurate, fast, and reliable. We used 10 sequences for EEG data acquisition for online analyses, but offline analyses showed that the green/blue flicker matrix was more effective than the white/gray flicker matrix by the eighth sequence. Further reducing the number of sequences to five still provided greater than 70% accuracy with a higher bit rate. The mean accuracy at the fifth sequence became lower than that at the tenth sequence, so if the users needed to complete their sentences by correcting misspelled characters, it would take a longer time (Townsend et al., 2010). The sequence times may be determined by individual user preference, as some prefer to control devices quickly with lower fidelity, whereas others prefer to communicate precisely and more slowly (Sellers and Donchin, 2006).

The severity of the patient impairment may also have implications for practical BMI use. Kübler and Birbaumer (2008) reviewed a number of BCI studies using P300, SMR, and slow cortical potential (SCP) and reported a relationship between physical impairment [subdivided into minor, moderate, major, locked-in state and complete locked-in state (CLIS)] and BCI performance. When they included CLIS patients, they found a strong correlation between impairment and BCI performance; however, after removing the CLIS patients, the correlation disappeared. Nijboer investigated the efficacy of a P300 BCI in eight advanced ALS patients (Nijboer et al., 2008) and showed that online BCI performance was not correlated with the degree of disability according to the ALS Functional Rating Scale (Cedarbaum and Stambler, 1997). Thus, for patients with ALS, it is suggested that BCI be applied before the onset of CLIS (Birbaumer, 2006; Kübler and Birbaumer, 2008). In the present study, we found no correlation between performance and ASIA impairment scale score (complete or incomplete) in SCI patients, nor did we observe a correlation between performance and time since injury. We previously reported that the BMI performance of subacute SCI subjects, whose time since injury was less than a year, was worse than that of chronic SCI subjects (Ikegami et al., 2009). Further investigation is required to determine the optimal time for applying BCI to individuals with SCI.

In conclusion, the P300 BCI system for environmental control and communication with a green/blue flicker matrix provided better accuracy than that with a white/gray flicker in individuals with cervical SCI, and future studies may aid the development of practical BCI for these individuals to expand their range of activity and communication.

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リハを支えるテクノロジー最前線

(11) 脳波による家電操作

神作憲司[1)]

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Keywords　BMI　BCI　環境制御　上肢アシストスーツ

はじめに

脳からの信号を計測し，それを利用して機器操作を行い，コミュニケーションの補助，生活環境の制御，運動の補助等を行おうとする，「ブレイン–マシン・インタフェース（Brain–Machine Interface；BMI）」もしくは「ブレイン–コンピュータ・インタフェース（Brain–Computer Interface；BCI）」とよばれる新技術が注目されている[1,2]．脳からの信号を利用して，コンピュータ，ロボット，義手，電動車いす等の機器を操作するといったアイデアは以前よりあったが，昨今の脳信号を計測，解析する技術の進歩や，システム脳神経科学の発展等を基として，研究が広く展開し始めた．本稿では，筆者らの開発しているBMI技術に基づいた環境制御システム等を紹介しながら，BMIがリハビリテーション分野に貢献する可能性について論じたい．

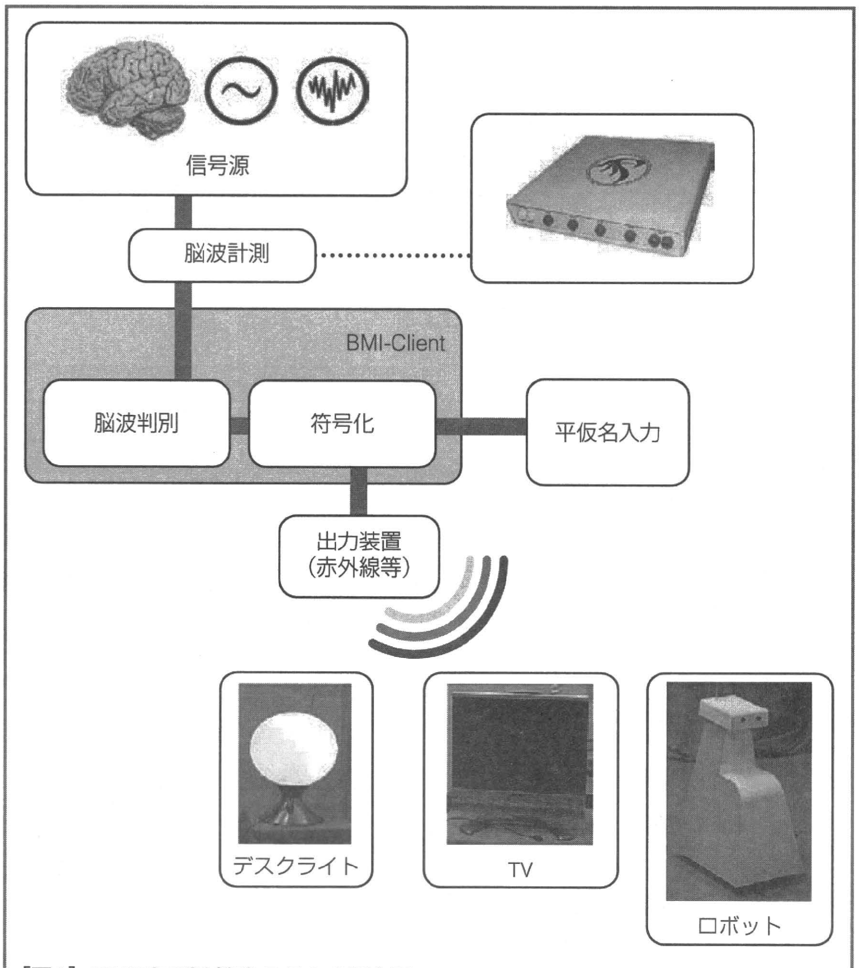
BMIとは

BMIは，脳からの信号を測定する電極等を留置するために手術を必要とする「侵襲型」と，手術を必要としない「非侵襲型」に分類される．手術を必要とせず，非侵襲的に脳からの信号を測定する手法としては，脳波（EEG），陽電子断層撮影（PET），機能的磁気共鳴画像法（fMRI），脳磁図（MEG），近赤外分光法（NIRS）等があげられる．脳波は，頭皮上の電極から比較的簡便に測定することができ，時間分解能も高いため，BMIで多く利用されている．脳波の空間分解能は低く，得られる情報に制限があり複雑な情報を引き出すことは難しいと考えられていたが，信号取得や解析の手法を工夫することでこうした点が改善されてきた．感覚運動の変換過程における脳波の周波数特性[3,4]や，P300等の認知機能を反映する成分[5,6]等が，脳波を用いたBMIの研究開発で着目されている．

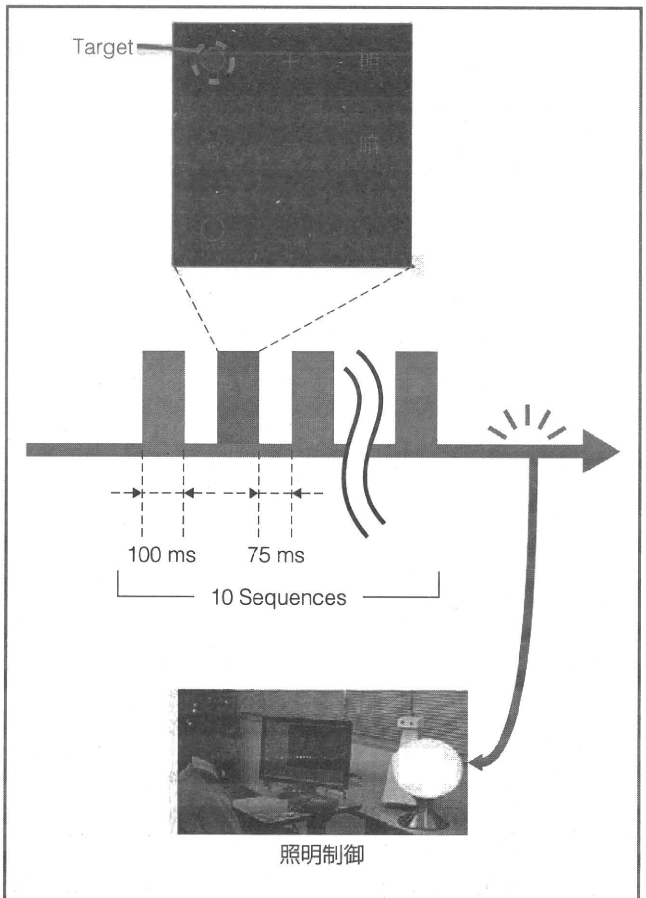
BMIの応用

■(1) BMIによる生活環境の制御

筆者らは，視覚刺激にて誘発された脳波信号を基に，ライトの点灯やテレビのチャンネル切り替えといった家電等の操作を行うシステムを開発した．このシステムでは，操作パネル上に配置した文字やアイコンから成る視覚刺激を提示しながら，頭皮上に装着した脳波電極から信号を計測し，それを解析することで，提示した文字やアイコンのうちどれを注視しているのかを判別し，その特定されたコマンドを赤外線で家電等の機器に送る．こうすることで，手足を動かさずに脳からの信号だけで機器を操作することが可能となる（**図1**）．操作パネルとしては，Donchinらによって提案されたP300スペラー[5,6]とよばれる方式を変更した．このP300スペラーでは，6×6マスのマトリクス上にアルファベットと数字を配置しており，マトリクス上のセルを1行または1列ずつ同時に強調表示するといった手法を用いることで，被験者が注視しているセルに特徴的な脳波信号を誘発し，これによって行と列をそれぞれ特定



［**図1**］**BMI型環境制御システムの概念図**



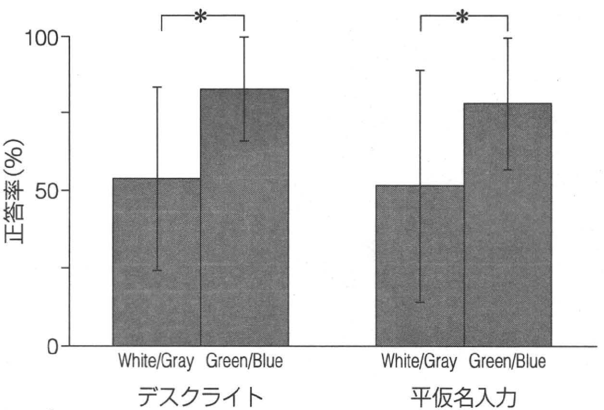
［**図2**］**実験の流れ**

する．筆者らは，C3/C4 レベルの頸髄損傷により四肢麻痺のある方に被験者となってもらい本システムを用いた実験を行い，これに成功した[7]．

■(2) 視覚刺激の工夫

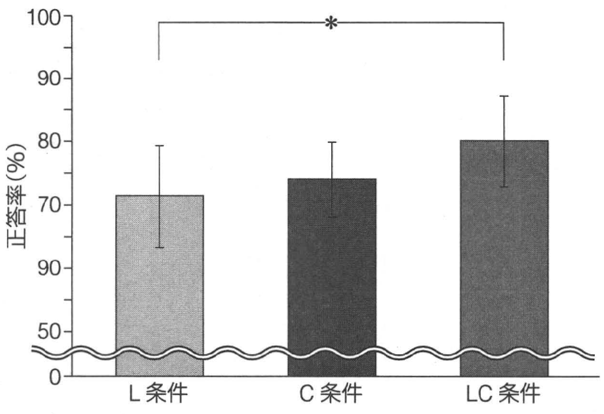
上記のBMI型環境制御システムを実用化するにあたり，機器の使用感や安全性，そして効率についても考慮する必要がある．Parraらは，緑と青の色変化がてんかんの発作に対してより安全と報告した[8]．これに基づき筆者らは，上記のシステムの操作精度について，従来の輝度変化と緑と青の色変化を用いたものの比較を行った．また，その使用感について視覚アナログスケールを用いた評価を行った．課題としてはデスクライトの制御と平仮名の入力を行った(**図2**)．

従来の輝度変化と緑と青の色変化を用いたものの比較を行ったところ，デスクライトの制御では精度が輝度変化では平均53.8%であったのに対し，色変化では平均82.8%，平仮名の入力では精度が輝度変化では平均51.7%であったのに対し，色変化では平均78.3%と，課題を問わず色変化を使用した場合に20%前後の精度の向上が有意に観察された(**図3**)．



*:<0.05

［図3］ デスクライト制御および平仮名入力の精度



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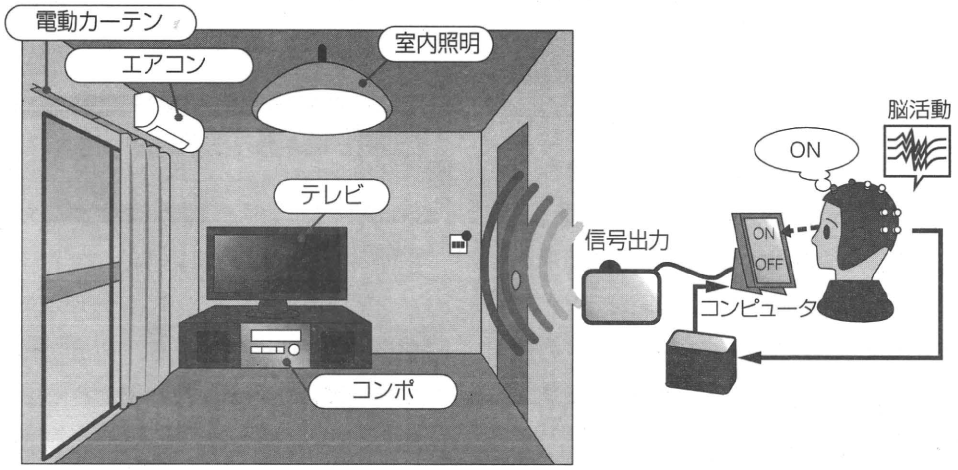
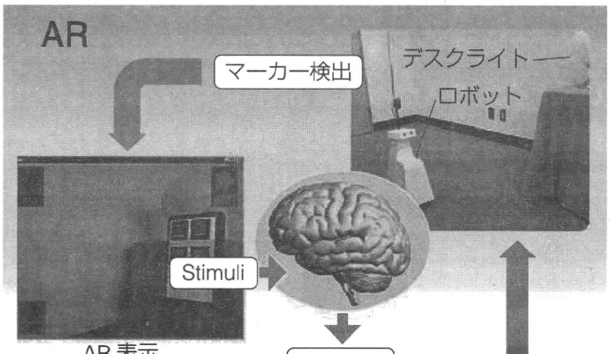
［図4］ 条件による精度の違い



［図5］ インテリジェントハウスの概念図



(Kansaku et al, 2010, 改変)[13]

［図6］ AR-BMIの概念図

また被験者別でみた場合，輝度変化で特に低い精度を示した被験者で40%程度という顕著な精度の向上が観察された[9]．また，使用感においても，色変化が有意に高い評価を得た[10]．

さらに視覚刺激の与える影響を詳細に調査するべく，従来の輝度変化（L条件），緑と青の等輝度での色変化(C条件)，色と輝度の両方の変化(LC条件)の3条件を用意し，特段のトレーニングを行っていない被験者に対して，平仮名の入力15文字分を各条件で行った．L条件とC条件では正答率に有意差は観察されなかったが，LC条件とL条件ではLC条件において有意に高い正答率を示した[11]（図4）.

■(3) 拡張現実(AR) をBMIと組み合わせる

こうしたこれまでに開発したBMI技術に基づき，脳からの信号で操作できるインテリジェントハウスの開発，さらにはインテリジェントホスピタルの開発へと展開させることも夢ではない[12]（図5）．その将来的な普及においては，使用可能なエリアの拡張が容易であることが望まれる．従来のBMI型環境制御システムでは，状況に合わせて適切な操作パネルを使用者に提示することは難しかった．そこで筆者らは，環境(位置や物)に情報を付与しそれを使用者に提示する技術であるAugmented Reality(AR; 拡張現実)技術とBMI技術とを融合させ，環境に応じて操作パネルを提示可能な「AR-BMI技術」を開