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Learning to control brain activity: A review of the production and control of EEG components for driving brain–computer interface (BCI) systems

Eleanor A. Curran[a,b] and Maria J. Stokes[a,*]

[a] *Research Department, Royal Hospital for Neuro-disability, West Hill, Putney, London SW15 3SW UK*
[b] *Department of Law, University of Keele, Staffordshire ST5 5BG, UK*

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Abstract

Brain–computer interface (BCI) technology relies on the ability of individuals to voluntarily and reliably produce changes in their electroencephalographic (EEG) activity. The present paper reviews research on cognitive tasks and other methods of generating and controlling specific changes in EEG activity that can be used to drive BCI systems. To date, motor imagery has been the most commonly used task. This paper explores the possibility that other cognitive tasks, including those used in imaging studies, may prove to be more effective. Other factors which influence performance are also considered in relation to selection of tasks, as well as training of subjects.

Keywords: Brain–computer interface (BCI); Cognitive tasks; Electroencephalography (EEG); Driving BCI systems; BCI subject training

1. Introduction

Brain–computer interface (BCI) technology has the potential to enable severely disabled people to drive computers directly by brain activity rather than by physical means. Research into BCI systems has mainly involved recording of electroencephalographic (EEG) signals using surface electrodes, although implanted electrodes have also been used (Kennedy et al., 2000).

Significant technological advances have occurred in the past decade towards developing a BCI system using spontaneous EEG activity (Babiloni et al., 2000; Birbaumer et al., 1999; Keirn & Aunon, 1990; Penny, Roberts, Curran, & Stokes, 2000; Pfurtscheller, Flotzinger, & Kalcher, 1993; Vaughan, Wolpaw, & Donchin, 1996; Wolpaw, McFarland, Neat, & Forneris, 1991; Wolpaw & McFarland, 1994; Wolpaw, Flotzinger, Pfurtscheller, & McFarland, 1997). Generation of the EEG activity used to drive BCI systems is usually achieved, at least initially, by the subject performing certain cognitive tasks. The subject then learns to control the cursor on a computer screen. Much BCI research has involved the development of powerful signal processing techniques to enable reliable and accurate control of the cursor by the EEG signals generated (McFarland, McCane, David, & Wolpaw, 1997a, 1997b; Penny & Roberts, 1999; Pfurtscheller, Flotzinger, & Neuper, 1994; Roberts & Penny, 2000; Wolpaw & McFarland, 1994; Wolpaw, Ramoser, McFarland, & Pfurtscheller, 1998).

The first International Meeting on BCI technology took place in Rensselaerville, New York in June 1999 and was organised by the BCI research team at the Wadsworth Center of the NY State Department of Health and State University of New York. Papers from groups attending this meeting were published in *IEEE Transactions on Rehabilitation Engineering*, June 2000; (as cited and listed in the references of the current paper). Different approaches to the training of subjects in the production and control of particular EEG signals were discussed. Research groups from New York and Tübingen favoured an approach that aims to train

* Corresponding author. Fax: +44-020-8780-4507.
E-mail address: mstokes@rhn.org.uk (M.J. Stokes).

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subjects to automatise the skill of controlling EEG components. Other research groups trained subjects to control EEG components by the performance of specific cognitive tasks.

The present paper reviews the status of BCI research regarding the methods of production and control of EEG components (to drive BCI systems), particularly those that utilise cognitive tasks. Details regarding choice of cognitive tasks, training instructions to subjects and reasons for choices of electrode placement are often lacking in studies in the literature. The range of cognitive tasks used is currently limited. The intention of the present review is to provide information from which to make choices regarding the neuropsychological as distinct from the technological aspects of the BCI system. In other words, focusing on the person interacting with the system. Directions for further research are also suggested so that the potential of BCI technology can be maximised in future.

2. Background neuropsychology and neurophysiology

A brief overview of some basic neuropsychological and neurophysiological issues relevant to BCI systems will be addressed in this section and include: the voluntary control of certain mental and brain activity, and the question of what type of skill may be required.

2.1. Voluntary control of thoughts and brain activity

The development of EEG-based BCI systems raises many questions concerning the three-way relationship between:

(i) the mental states and processes that provide the content and motivation for the communication
(ii) the brain activity, as recorded by EEG, being utilised to drive the device
(iii) the voluntary manipulation and control of that brain activity.

Subjects in BCI experiments are asked to produce and control changes in particular EEG signals by thinking about specific things and/or by concentrating on willing a cursor to move. This involves an entirely new form of control for a human being over his or her brain activity, with the intention of using such activity as a new form of communication. Such a process would provide "the brain with wholly new communication and control channels" (Vaughan et al., 1996). Leaving aside the question of whether it is the brain that communicates or the person, we can say that using a BCI system requires deliberate or voluntary control over a type of brain activity that a person is usually unaware of and unable to recognise or sense.

One possible metaphor that could be applied is the control that we have over motor tasks. We are unaware of how and when our brain sends messages to our muscles, how the muscles work, in what order and so on. Despite being unaware of exactly how movements take place, they are under our control. They are, in other words, voluntary, even though they sometimes require little or no conscious effort or 'attention,' for example when riding a bicycle. The acquired skill of riding a bicycle, therefore, can be voluntary but automatic.

2.2. Automated activity versus conscious mental effort

Discussion at the above mentioned BCI conference in New York in June 1999 did not reach a consensus regarding whether the skill of controlling a cursor with EEG activity can or should become fully automated. One possible advantage of an automated skill is that once it becomes automatic, it requires little or no conscious effort and may therefore reduce mental fatigue. However, Kennedy et al. (2000) have reported that even automated control of the cursor is less effective when the subject is fatigued and that repeated efforts to control the cursor results in fatigue. The Tübingen group also reported fatigue as a problem when subjects aim to respond more quickly (Kübler et al., 1999). In BCI experiments where the skill is not automated, great concentration and mental effort are required of the subjects and fatigue has been found to be a problem (personal experience of the authors). Other psychological factors such as distractions are also likely to be a problem. Some BCI researchers argue that mental effort is required to generate adequate signals, whilst others have shown that, after sufficient training, subjects can perform other tasks such as listening to and answering questions at the same time as moving the cursor (Miner, McFarland, & Wolpaw, 1998). This demonstrates that the EEG control no longer requires a subject's full attention.

Some BCI experiments that clearly involve conscious mental effort are those that train the subject to change their EEG signals by performing conscious 'cognitive tasks' (Babiloni et al., 2000; Penny et al., 2000; Pfurtscheller et al., 1993). Furthermore, in some studies where the subject has been trained to acquire *automatic* control over the EEG activity, they still used what might be termed cognitive tasks (i.e., motor imagery) initially, when learning to gain control over the cursor (Birbaumer et al., 1999; Wolpaw et al., 1991; Wolpaw & McFarland, 1994; Wolpaw et al., 1997). There is also some anecdotal evidence suggesting that subjects who have the ability to control the EEG automatically will still return to using cognitive tasks on occasions when the automatic skill fails them (personal communication with subjects).

2.3. Voluntary control of a BCI device

As mentioned above, there is disagreement as to whether the skill of controlling a cursor with EEG activity can or should become fully automated. There is agreement, however, that the subject must acquire *voluntary* control of whatever EEG components are used to operate the BCI system. Research has not yet established conclusively what type of skill or skills this involves. Some researchers suggest that cursor movement appears "to become similar to conventional motor performances" (Wolpaw & McFarland, 1994). If this is correct, then, like ordinary motor activity, BCI cursor control would develop automatic components, whilst remaining voluntary.

Given that use of a BCI device must be voluntary, however, we need to be able to tell whether the subject *intends* to activate the device (Vaughan et al., 1996). With the use of spontaneous EEG that also occurs naturally during, for example, movement and movement planning, there is a danger that a subject could activate the device unintentionally. This could not be resolved by having a simple on/off switch because the on/off switch could also be activated unintentionally. The switch would have to draw to the subject's attention that it had been switched on, by, for example, a noise. This might work for a pure communication device but if the BCI system were to be used for environmental control systems, the on/off mechanism would have to be fail-safe. This problem highlights the potential difficulty and complication of using brain activity that is not normally controlled consciously, for voluntary communication and/or use of environmental control systems. Cognitive tasks and other means used for controlling BCI systems are reviewed below, but we will first take a brief look at non-BCI studies of the EEG signals produced by various cognitive tasks.

3. EEG research on cognitive tasks

Research on the relationship between cognitive tasks and EEG activity has produced an extensive literature, which is beyond the scope of the present review but is essentially variable in its conclusions. There are reasons for questioning the reliability of apparent correlations between individual cognitive processes and accompanying changes in EEG signals. One difficulty lies in successfully pinning down which cognitive processes are taking place during the performance of a particular cognitive task and where in the brain the activity is located; another concerns whether factors outside the immediate cognitive processes may be causing the changes in signals. For example, factors such as memory, concentration, attention and the difficulty of the task (cognitive load) have been shown to affect the changes in EEG signals (Gevins, Smith, McEvoy, & Yu, 1997; Gevins et al., 1998; Holländer, Petche, Dimitrov, Filz, & Wenger, 1997; McEvoy, Smith, & Gevins, 1998; Smith, McEvoy, & Gevins, 1999). This latter difficulty has implications for BCI research where factors such as attention and cognitive load do not (to date) appear to have been seen as relevant variables. Some recent papers have shown evidence, for example, that alpha activity is affected by changes in task difficulty and practice (Gevins et al., 1998; McEvoy, Smith, & Gevins, 2000; Smith et al., 1999). This may be significant for those BCI researchers using changes in alpha rhythm activity to drive BCI systems. It need not be a disadvantage, however. Being aware of additional factors such as attention and load, and how they affect the signals could provide further ways of training subjects to control parts of their EEG activity.

The emotional state of the subject will also affect the signals produced during performance of cognitive tasks. The findings of Bartolic, Basso, Schefft, Glauser, and Titanic-Schefft (1999) suggest that the performance of cognitive tasks may be affected by mood. After inducing euphoria and dysphoria in members of a group of right-handed women, they observed that verbal fluency (left hemisphere, frontal lobe) was better in those in a euphoric state, while figural fluency (right hemisphere, frontal lobe) was better in those in a dysphoric state.

Gender is another factor that EEG research would suggest may be a variable in the performance of cognitive tasks. In normal adults performing verbal memory tasks for example, Volf and Razumnikova (1999) showed that there are significant differences in EEG activity according to gender. This supports less recent research, for example by Davidson, Schwarz, Pugash, and Bromfield (1976) that showed differences between males and females in right-hemisphere activation during emotional versus non-emotional trials, with females showing greater relative right-hemisphere activation. One cognitive task that has been constantly shown to be performed better by males than females is the mental rotation of an object in space (Pezaris & Casey, 1991), with the exception of a group of right-handed girls, with left-handed male relatives, who have been shown to adopt "masculine" strategies for solving spatial tasks.

Consideration of the different components of a cognitive task in relation to EEG activity are discussed below, as well as distinguishing between the signals produced by different tasks (see 'Breaking Down Tasks into their Components').

Recent EEG research has also tended to show that during the performance of cognitive tasks many different parts of the brain are activated and communicate with one another, thus making it difficult to isolate one or two regions where the activity will take place (Holländer et al., 1997; McEvoy et al., 1998). Holländer et al. (1997) expressed it in the following way:

> *up until recently, neurology was dominated by localisatory thinking. Language and other so-called 'centers' were considered to be centres of command*

controlling the respective functions. Today there is general agreement that, instead, for every brain function numerous brain regions must act together (p. 177).

The complexity of the relationship between EEG activity and cognitive processes has obvious implications for both the selection of electrode sites and, again, the use of cognitive tasks for BCI systems.

4. Cognitive tasks used for generating and controlling EEG activity to drive BCI systems

In much BCI research to date, subjects used cognitive tasks to generate EEG activity, which was then used to operate a BCI system. Little research has been conducted within BCI studies on the cognitive tasks themselves, or on their role in the successful operation of a BCI system.

Most BCI studies which used cognitive tasks chose motor imagery because it produces changes in EEG signals that occur naturally in movement planning and are relatively straightforward to detect. The signals are generated in the motor cortex and can be recorded from scalp electrodes over central head regions (Babiloni et al., 2000; Penny et al., 2000; Pfurtscheller et al., 1993). Motor imagery has been shown to be effective in BCI research for controlling and moving cursors (Babiloni et al., 2000; Birbaumer et al., 2000; Penny et al., 2000; Pfurtscheller et al., 1993).

4.1. Motor imagery tasks used by different groups and the electrode sites used

Cognitive tasks using motor imagery have been employed by BCI researchers in different laboratories in Europe. Even some of the BCI research groups who did not use cognitive tasks reported that motor imagery was used by their subjects as a way to produce the EEG activity in the early stages of training (Birbaumer et al., 1999; Wolpaw et al., 1991; Wolpaw & McFarland, 1994).

Rome group. The research group based in Rome have used three motor imagery tasks: imagined left hand movement, imagined right hand movement and imagined right foot movements. In one study, five healthy subjects were asked to imagine the movement of the right middle finger or the left middle finger for a period of 10 s (Babiloni et al., 1999). As a control they were also asked to perform actual right and left middle finger extensions for periods of 10 s, and 10 s of rest activity (trying to relax with eyes open) was also recorded.

The degree to which EEG activity correctly reflected right or left imagined finger movements was termed the recognition score. Twenty-six surface EEG electrodes were placed over the scalp according to the 10–20 international system. Recognition scores were, however, recorded using fewer electrodes. The team concluded that:

> *[t]his study has shown that six or nine electrodes, placed over fronto-centro-parietal areas, are sufficient to detect two mental states related to imagined movements with the SSP (signal space projection) technique* (Babiloni et al., 1999, p. 38).

It was also found that recognition scores of the imagined movements increased if all of the 8–30 Hz band was analyzed rather than separating the alpha and beta frequency bands.

Graz group. The Austrian team working in Graz, used specific motor imagery to produce and control the EEG activity that drives their BCI system. Three tasks were used; planned/imagined left hand movement, planned/imagined right hand movement, and planned/imagined foot movement. Subjects were asked to start imagining hand movement following the appearance of a visual cue; depending on the direction of the arrow that appeared on the screen, the subject imagined either left or right hand movement. This was performed with and without feedback. Continuous feedback was provided in the form of an arrow on the screen moving to the left or right as the subject concentrated on imagining left or right hand movement (Birbaumer et al., 2000).

The Graz group used two different electrode configurations, one using bipolar C3–C3′ and C4–C4′ and the other using 27 electrodes located in a cap and placed over central areas (Birbaumer et al., 2000).

4.2. Motor imagery and non-motor cognitive tasks

Only one group has published results using formalised motor imagery, together with other non-motor cognitive tasks to drive a BCI system.

Oxford/London group. This group involves collaboration between the Department of Electrical Engineering, at the University of Oxford, and the Royal Hospital for Neuro-disability in London. They have used two cognitive tasks and a baseline task of relaxation in an online BCI system (Penny & Roberts, 1999; Penny et al., 2000). One of the cognitive tasks used motor imagery; the subject was asked to imagine opening and closing their right or left hand (depending on hand dominance). The other task involved mental arithmetic; the subject was instructed to subtract sevens successively from a three digit number (Penny et al., 2000). The mental arithmetic task was selected from the cognitive tasks used by Keirn and Aunon (1990) who examined five different mental tasks to see if they would produce measurably different EEG responses that could then be used to distinguish between the tasks. The Oxford/London group has used feedback in experiments to date, i.e., the cursor moved up or down on a computer screen, towards a target, as the subject performed the cognitive task.

Following pilot studies using several channels on the 10–20 international system, only three electrodes were used, placed at C3′ and C4′ (i.e., 3 cm behind C3 and C4 in the 10–20 international system) with a third reference electrode placed over the right mastoid (Penny et al., 2000).

5. The operant conditioning method of training subjects to produce and control EEG components to drive BCI systems

Some BCI research groups have used a different approach to the training of subjects that does not employ the use of well-defined cognitive tasks. They used instead an 'operant conditioning' approach (Birbaumer et al., 1999) with the intention of training subjects to control the cursor automatically (Birbaumer et al., 2000; Wolpaw et al., 2000). This method differs from that using cognitive tasks in that the subjects may think about anything (or nothing) so long as they achieve control of the cursor. They are usually asked just to try to move the cursor on the computer screen, the idea being that with the aid of feedback the subject's brain learns to control EEG components in an appropriate way. Over many sessions the subject acquires the skill of controlling the movement of the cursor without being consciously aware of how this is achieved. As mentioned earlier, this is sometimes compared to learning the skill of riding a bicycle or playing tennis. Employment of the skill is voluntary but automatic (the tennis player *does* consciously decide to try and return the serve but *does not* consciously decide where to place the racket, rather, he or she does it automatically).

5.1. New York group

BCI researchers at the Wadsworth Center, Albany, New York, did not instruct subjects to use formal cognitive tasks but instead asked them to concentrate on moving the cursor (Wolpaw et al., 1991; Wolpaw et al., 1997). The aim of this approach is to train the subjects to produce and control components of their EEG automatically rather than by the conscious performance of cognitive tasks. Feedback is used i.e., the cursor moves towards the target when the subject succeeds in producing appropriate EEG components. The subject, after training, should then be able to decide to move the cursor on the screen and then do so, without understanding exactly how, just as they might decide to lift a glass of water and then do so without being aware of how and which muscles to move etc. The group reported success in this type of training for driving a BCI system, noting that as training progresses the skill becomes automated:

> *...EEG-based cursor control appears similar to more conventional skills which, once learned, no longer require intense concentration.* (Vaughan et al., 1996, p. 429).

This training method does not ignore cognitive tasks altogether, however, as motor imagery is, reportedly, often used in the early stages of training to produce and control the EEG activity:

> *Subjects reported that they adopted various strategies, such as thinking about a certain activity (e.g., lifting weights) to move the cursor down, and thinking about relaxing to move it up. As training progressed, several reported that such imagery was no longer needed.* (Wolpaw et al., 1991, p. 256).

Motor imagery is thus seen as useful initially to help the subject to start generating the EEG components but it should cease to be necessary as the skill of producing and controlling the EEG components becomes automated. Anecdotal evidence suggests that the ability to acquire automatic control of some EEG activity may vary between subjects, however. One subject reported a continuing need to use motor imagery, while another reported good automatic control that occasionally failed, in which case a return to the use of motor imagery was found to be effective in regaining control of the cursor (personal communication with subjects-EC).

In the New York studies, although EEG components from only one or two locations were used to control cursor movement online, data were collected from 64 locations for offline analysis. The EEG component recorded that has been shown to be susceptible to conditioning is the mu rhythm, which is the 8–12 Hz activity (alpha rhythm) recorded over primary sensory and motor cortices (Wolpaw & McFarland, 1994).

5.2. Tübingen group

The German group, based at Tübingen, also aimed to induce an automated skill in their subjects. Using the slow cortical potentials (SCPs) of the EEG, 'operant conditioning' was used to bring them under the voluntary control of the subject (Birbaumer et al., 1999). Feedback training was used and the subjects were given tasks such as trying to move the cursor towards a target after hearing a tone. Two tones of different pitches were used, following each other in intervals of two seconds, the 2-s phase between the low-pitch and high-pitch tone providing the 'active phase' during which the ball (cursor) on the screen should be moved, while the phase between the high-pitch tone and the low-pitch tone provided the 'baseline phase,' during which the cursor remained still. This training was performed with both healthy subjects and almost completely "locked-in" paralyzed patients (Birbaumer et al., 2000).

This group also reported, however, that imagery could be used as part of the subject's strategy to achieve control of the EEG components:

> *Using an imagery strategy, both patients were better able to produce positivity rather than negativity* (Birbaumer et al., 1999, p. 297).

Electrode placement for the Tübingen studies included EEG recordings from Cz, C3, and C4 on the 10–20 international system. SCP shifts from the vertex (Cz) served as the primary signal. Cz was recorded against both A1 (left mastoid) and A2 (right mastoid), (see Birbaumer et al., 2000 for more details).

The difference between the 'operant conditioning' method of training subjects and that using cognitive tasks, is summarised in the following way by the Austrian group:

> *"A further difference between the two BCI prototypes is that the New York BCI is internal-paced and unspecific while the Graz BCI is external-paced and specific. Internal-paced here means that the subject determines the start of 'mental activity' himself while in the external-paced system in Graz a stimulus is given to indicate when the 'mental activity' should start. The term 'specific' is used here to indicate that in the Graz BCI the EEG is recorded over specific cortical areas, the motor and pre-motor areas, which are known to be involved in motor processing. In this sense the New York BCI uses 'unspecific' electrode locations because **some undefined mental process is used to control the movement**."* (Pfurtscheller et al., 1993, p. 297/298, ***our emphasis***).

6. Cognitive tasks used in imaging studiesMRI and PET

In recent years, research into brain function has benefited from significant advances in the use of the scanning techniques of positron emission tomography (PET), and functional magnetic resonance imaging (fMRI). These techniques have enabled researchers to pinpoint the location of the brain areas that are activated during the performance of particular cognitive tasks.

An examination of research in this field might prove helpful to BCI researchers in providing more (geographically accurate) evidence of the location(s) and extent of activity in the brain that is associated with the performance of the cognitive tasks they have chosen.

7. Breaking down tasks into their components

Many questions concerning the cognitive tasks remain to be answered. Do some components of cognitive tasks produce stronger EEG signals or different characteristics than other components? Which mental states and processes actually generate the EEG signals that can be utilised to drive the BCI device; those associated with the cognitive task being performed or others that are a bi-product of performing the tasks such as attention or cognitive load? Motor imagery has been used with considerable success as a cognitive task in BCI experiments but the motor imagery tasks themselves have yet to be investigated in the context of BCI systems. Subjects are often asked to imagine or think of moving their hand (Babiloni et al., 2000; Neuper, Schlögl, & Pfurtscheller, 1999; Penny et al., 2000), for example. This task can be understood in one or several of the following ways:

(a) remember or bring to mind feeling of hand moving
(b) visualise own hand moving
(c) visualise another's hand or abstract hand moving
(d) combine remembered feeling of hand moving with visualisation of hand moving
(e) form intention to move hand (whilst ensuring that it does not move)

Do each of these ways of performing the task generate the appropriate signals to the same extent or do some generate them with greater intensity or more quickly than others? Are such fine distinctions under our control when we perform cognitive tasks? Different ways of performing the tasks employ different mental processes e.g., visualization as opposed to memory retrieval. There are also related questions concerning how easy they are for the subjects to perform and whether the subject is practiced in their performance. Also, all of these factors may vary between individuals.

There is some anecdotal evidence for the significance of a distinction that can be drawn between the use of the following perspectives in achieving motor imagery (Decety, 1996):

- *a first person perspective*, which relies on motor-kinaesthetic information processing (sense of movement/muscular activity, as when feeling one's hand move, as in a, above)
- *a third person perspective*, which relies on visuo-spatial information processing (seeing or picturing a hand moving, as in b or c, above)

There is also some evidence from sports psychology, that first person kinaesthetic imagery is more effective than third person imagery when the purpose of the imagery is to improve performance of real movement (Decety & Ingvar, 1990). This is supported by anecdotal evidence from BCI experiments that the first person perspective may be most effective for cursor control and subjects are therefore encouraged to use it (personal communication with subjects).

Distinctions such as that between the use of a first or third person perspective could be helpful for BCI researchers and could provide a starting point from which to investigate the component thoughts and mental processes that can be included in the motor imagery and other cognitive tasks.

7.1. Other research on cognitive tasks to produce discernible changes in EEG signals

Research and a review in 1990 by Keirn and Aunon, and continuing work on the same data by Anderson and Sijercic (1996), defined five cognitive tasks that generate EEG signals that can be differentiated with some success. The five tasks were: a *baseline task*, for which subjects were asked to relax; a *letter task*, in which the subject was instructed to mentally compose a letter to a friend or relative without vocalising; a *mathematical (math) task*, for which subjects were given a non-trivial multiplication problem to solve, such as 49 times 78; a *visual counting task*, for which subjects were asked to imagine a blackboard and visualise numbers being written on the board sequentially; and a *geometric figure rotation task*, for which subjects were asked to visualise a particular three-dimensional block figure being rotated around an axis. When subjects performed the various tasks they were correctly classified by EEG activity according to each task with varying degrees of accuracy.

Some surprising results, however, showed that there were

> *potential confusions that the [neural network] classifier might make... (from) the relatively high responses of an output unit for test segments that do not correspond to the task represented by that output unit*. (Anderson & Sijercic, 1996, p. 410).

During the mathematical tasks, output value of the math unit was high, as expected, but it was also relatively high during count segments. Similarly, the output of the count unit was relatively high during letter segments as well as during the count segments.

In other words, classification of each cognitive task according to the EEG signals recorded during performance of that task has been achieved but then it becomes apparent that there is some overlap between some of the tasks. These results suggest correlations between certain aspects of different cognitive tasks. Subjects performing the mathematical task and the count task may use visualization of numbers in both cases. The count task and letter task may both require visualization of writing. These interesting results highlight the fact that differentiating between cognitive tasks on the basis of the EEG signals recorded during their performance is not straightforward and calls for more detailed research on the cognitive tasks.

Identifying pairs of cognitive tasks which produced distinct EEG characteristics at the same recording site would have practical benefits. A suitable pair could then be selected for a subject and only single channel recordings would be necessary.

7.2. Historical note

The choice of cognitive tasks investigated by Keirn and Aunon (1990) and Anderson and Sijercic (1996) was inspired by work carried out in the 1960s and 1970s that examined changes in the EEG as part of ongoing investigations of the theory of hemispheric specialization (Dumas & Morgan, 1975; Galin & Ornstein, 1972; Keirn & Aunon, 1990). Evidence had been gathering to support the view that certain cognitive functions were predominantly dependent upon either the left or the right hemisphere. Studies of brain-injured patients had shown that damage to the left hemisphere was particularly associated with interference in the areas of language processing and analytical and mathematical tasks, whilst damage to the right hemisphere was associated with interference in the areas of spatial relations (Galin & Ornstein, 1972). Some of the research exploring these findings used EEG recordings taken while subjects performed cognitive tasks designed to isolate the cognitive skills associated with a particular hemisphere.

When Gevins et al. (1979) tested the theory of hemispheric specialization they used, in one experiment, the following tasks.

(a) mental rotation of block structures (a spatial task)
(b) addition of a column of six to eight signed integers (logical task)
(c) letter substitution (logical task)
(d) visual fixation on a spot (a control task)

If we compare these cognitive tasks with those tested by Keirn and Aunon (1990) and Anderson and Sijercic (1996) we can see the similarities, and indeed Keirn and Aunon (1990) refer to the origin of their cognitive tasks in this previous research:

> *It was not the goal of this research to prove or disprove the theory of hemispheric specialization; however we chose mental tasks based on research in this area in hopes of producing measurably different responses in the EEG that could be used to distinguish between the various tasks* (Keirn & Aunon, 1990, p. 1209).

8. Other cognitive and psychological factors

It has already been mentioned above (see Section "EEG Research for Cognitive Tasks") that factors other than the cognitive tasks themselves, such as cognitive load, attention and practice, may affect the EEG signals that are generated while the cognitive task is being performed. It follows from this that the subject's control over the EEG signals being used to drive the BCI system may also be affected by these other factors.

8.1. Mental states and external factors influencing EEG activity

Other mental states and processes that might affect the ability of the subject to attain and/or maintain voluntary control of the EEG signals could include:

(i) concentration/focus
(ii) other thoughts/control of thoughts
(iii) frustration
(iv) other mental/emotional states (e.g., depression)
(v) relaxation
(vi) fatigue
(vii) distractions/interruptions
(viii) motivation/desire
(ix) intentions

Again, there is some anecdotal evidence about the effect of some of these factors. Informal reports from subjects have suggested that (i), (ii), and (iii) have been experienced as problematic (by personal communication Dr. W Penny, with permission). Depression and/or lack of motivation has been found to be a problem with some disabled patients (Birbaumer et al., 1999). As mentioned earlier, fatigue has been shown to be a factor in the training of subjects in the use of BCI systems, as well as evidence that emotional state may affect the performance of cognitive tasks and EEG activity (Bartolic et al., 1999). There is also some evidence to show that subjects who have been trained to acquire automatic control of EEG components can tolerate distractions by, for example, answering verbal questions while maintaining cursor control (Miner et al., 1998), but if this technology is to be applied to environmental controls for disabled people, more thorough investigation is required in view of the safety implications.

8.2. Training time

The length of time required to train subjects to acquire the necessary control over the EEG components has been cited as a cause for concern by some groups. Wolpaw et al. (1997) reported improved accuracy of EEG control by the final session for four subjects tested over 10–15 sessions (each subject participated in 26–86, 1-h sessions). Penny and Roberts (1999) reported that training time can be speeded up when the task pairings are changed in such a way that better initial discrimination between them is achieved and when adaptive pattern recognition methods are used.

Kübler et al. (1999) reported that three out of five healthy subjects who participated in prolonged training (the five had been selected from thirteen subjects after one session), demonstrated significant self-control of the EEG components after 10–13 sessions. Out of three patients with amyotryophic lateral sclerosis (ALS), two of whom were artificially ventilated and virtually completely paralyzed, all three achieved significant SCP control after 20–40 sessions. After 40–120 sessions, two of the patients had sufficient control to use the device to write single words and combinations of three to four words using a dichotomic spelling structure (Kübler et al., 1999).

The Tübingen group also reported that one ALS patient was successfully trained initially but then lost control of the EEG components, in this case changes in SCP, after a change in the training program and was unable to regain it (Birbaumer et al., 1999). Subject compliance could be poor with such long training periods. In contrast, the Austrian group reported faster learning times, which they attributed to their system adapting to the individual, as well as the individual adapting to the system

> *...in Graz the system adapts to the users which reduced the time for reasonable results from weeks to some days* (Pfurtscheller et al., 1993, p. 297).

After four half-hour sessions they reported reasonable accuracy, though it should be noted that this initial testing was on only one subject. In a more recent study looking at the effect of continuous feedback on training, they reported improved success rates for four subjects after 'several' of a total of eight sessions. These subjects were already 'trained' to some extent, however, as they had already taken part in previous studies (Neuper et al., 1999).

9. General discussion

As reported in Section 1 much BCI research has been concerned with the development of complex signal processing techniques that make it possible to use differences between EEG signals to drive a computer. Work in areas related to the person using the BCI system is also required.

9.1. Training of subjects

The next stage of developing a BCI system, training subjects to consistently and reliably produce and control changes in some of their EEG output, is now being explored with some success. However, both the nature of the skill being acquired and the process by which it is learned, are far from clearly understood. Partly as a consequence of this, the method of training varies between research groups, the length of time required for training is often unacceptably long and not all subjects are able to acquire and maintain the necessary control over the EEG signals produced.

9.2. Selection of appropriate cognitive tasks

The research groups who train subjects in the use of cognitive tasks have found motor imagery tasks to be quite effective, but there has been little examination of the imagery tasks themselves and how they might be refined and improved. It may be appropriate to take a step back in BCI system development and pay more attention to the tasks used by the subject to control the system. Other cognitive tasks used have been taken from research into hemispheric specialization rather than from any research in the area of BCI development. There may be cognitive tasks that would be as effective or more effective for driving BCI systems than those that have been used so far. It has been suggested in the present review, for example, that some of the cognitive tasks that are used in imaging studies (PET, fMRI) might prove to be effective for BCI training. There is, therefore, much work required to develop a range of well-defined, easily learned cognitive tasks that are shown to enable all or most subjects to produce and control EEG signals that can be used to drive a BCI system.

There is also the possibility that preference for, and the effectiveness of, different cognitive tasks may vary between individual subjects (Pfurtscheller et al., 2000), which is another reason for building a broader range of reliable tasks. Some tasks may be inappropriate for certain groups of subjects e.g., motor imagery may be difficult for a person who has been paralyzed for many years, or, indeed from birth. Visual tasks would probably be inappropriate for some visually impaired people, such as those who have been totally blind since birth. Unless a variety of tasks has been investigated for reliability and made available to subjects, BCI technology may have limited value for disabled people. All of the tasks available for subjects should be well-defined, unambiguous, easy to perform/concentrate on and as effective as possible for bringing about the voluntary production and control of the required changes in EEG signals.

9.3. Skill required for driving BCI systems

There is still no consensus in BCI research about the kind of skill or skills that must be acquired in order to successfully drive a BCI system. As reported in this review, some research groups argue that the skill, once learned, becomes automatic while others use cognitive tasks to, as it were, manually produce the required EEG signals. Again, further research is required to settle this important question. The two methods of training outlined above, i.e., that using cognitive tasks and that using 'operant conditioning' or 'implicit learning' to automatise the skill, are not as separate as they may seem. Both groups using 'operant conditioning' also reported subjects using motor imagery, in the early stages of training (Birbaumer et al., 1999; Wolpaw et al., 1991). Because there is a link between them, continuing research may shed light on the question of the nature of the skill really being developed.

More extensive research into the training method that uses cognitive tasks, for example, may show that after a long enough period of training, subjects find that they no longer always need to use the cognitive tasks to achieve cursor control; they might find that they can achieve more accurate control simply by concentrating on moving the cursor. Similarly, those attempting to train subjects to move the cursor automatically may find that they continue to revert to using mental imagery as a strategy for cursor control. It may also be the case that long-term training leads to changes in effective control of the cursor as the brain adapts to the task it has been set. As with cognitive tasks, any method of instruction to subjects should be clearly defined and standardised, so that changes such as these will be noted.

9.4. Potential implications of BCI technology for disabled people

The implications for the clinical application of BCI technology are significant and success depends on appropriate research. Enabling or improving communication would not only improve contact between severely disabled people and those around them but could also allow them to become (more) involved in making decisions about their lives; this having obvious ethical and legal implications. Other possibilities include controlling wheelchairs and various environmental control systems. BCI technology therefore has the potential to provide severely disabled people with greater independence, increased control of their environment and their own lives, and hence also improved quality of life.

If subjects are to be successfully trained to drive BCI systems with sufficient accuracy to enable the safe and reliable operation of equipment and environmental controls, as well as devices solely for communication, then the training process needs to be more fully understood. Further research is required to establish the extent (and possibly the limits) of the control over spontaneous EEG activity that can be acquired by an average subject. As has been suggested in the present review, one area that would particularly benefit from more research is that of the methods used by subjects to drive the BCI system.

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