BCIs in Multimodal Interaction and Multitask Environments: Theoretical Issues and Initial Guidelines

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Abstract. The development of Brain Computer Interfaces (BCIs) enters a phase in which these devices are no longer restricted to applications in controlled, single-task environments. For instance, BCIs for gaming or high-end operator stations will function as part of a multimodal user interface in a multitask environment. This phase introduces new issues that were not relevant for the development of the initial special-use applications and we should address these issues systematically. In this paper, we will present the potential conflicts and how models of information processing can help to cope with these. We will conclude with providing guidelines.

Keywords: BCI, BMI, HCI, guidelines, hybrid BCI, information processing, multimodal, user interface, theoretical models.

1 Introduction

The initial development of Brain Computer Interfaces (BCIs) focused on providing users with special needs a way to communicate when other interaction means failed. However, there are also several good reasons to consider BCIs for healthy users, for instance to make control or communication more intuitive or reduce the risk of overloading sensory modalities or the motor system [1]. As a result, the scope of BCI applications under investigation expands rapidly and starts to include applications for gaming and adaptive automation.

For users with special needs, a BCI is often developed as the only interaction device and used for a specific communication task performed in isolation. In more complex situations, a BCI is part of a multimodal user interface and may be used in a multitask situation in which the user performs different tasks sequentially or even in parallel. This introduces relatively new user-system interaction issues and here we aim to have a closer look at for instance the (human information processing) models relevant for these situations. Appropriate integration of BCIs in multimodal interaction and multitask environments is a prerequisite for successful BCI applications for healthy users [2].

The expanding scope of BCI applications also requires reconsidering common BCI definitions. The assistive technology community often uses the strict definition provided by [3]: A BCI is a communication and control system that does not depend in

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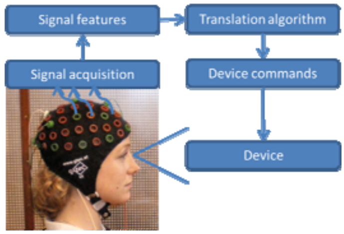

Fig. 1. Classic view of a BCI systems from the assistive technology approach

any way on the brain's normal neuromuscular output channels, that provides real-time interaction and includes feedback of the outcome to the user. We propose a broader definition more adjusted to the HCI community: "*a BCI uses signals from the brain to control a device or the interaction between the user and a device (near) real time, and/or provides signals directly to the brain to either communicate information or alter brain activity*". This definition includes systems that use brain signals to assess the user state for instance to adjust the task allocation or interaction modality between user and system. As such, brain signals can be considered an expansion of the set of physiological measures already used in user-system interaction such as heart rate variability. Also, BCIs can either refer to communication from the brain to a system, or vice versa (sometimes referred to as Computer Brain Interface, CBI), or both. However, the vast majority of current BCIs for healthy users uses communication from the brain to a device only.

Zander and colleagues [4] made a useful distinction between active, reactive and passive BCIs, based on the user's effort and task to control the BCI. In active BCIs, users actively generate specific brain signals to give a specific command, for instance by doing mental calculation or imaginary limb movement. Reactive BCIs do not require active generation of brain signals but interpret the brain's automatic reaction to so-called probe stimuli. The user can modulate this reaction pattern by modulating attention, which can be used to select a specific probe stimulus. Finally, a passive BCI analyses brain signals without the user needing to perform specific mental tasks, but uses neural correlates of constructs such as engagement, mental workload and drowsiness [5].

Figure 1 depicts the classic view of a BCI. The user actively generates a specific brain pattern (e.g. motor imagery). A sensor system (e.g. EEG) acquires and processes the brain signals followed by extraction and classification of the signal features by computer algorithms (see [6] for a review). The results are translated into device commands and executed by the device (e.g. a wheelchair) and the user can perceive the result. In this classic setup, there is only one task and no other interaction channels between user and device. We will discuss the extensions: to a dual-task situation, to combining two BCIs and to the integration with other user-system interaction modalities.

2 Challenges for the Use of BCIs in a Dual Task Environment

Figure 2 uses a model of a (closed-loop) user-system interaction in which the user is simply modeled with a perception, cognition, and action step. The user perceives system information (this phase -arbitrarily- includes bottom-up processing in the brain, i.e. by the sensory cortices), further processes this information in the brain (i.e., higher order cognitive processes) and performs an action affecting the system. With this latter phase we exclusively refer to the peripheral motor system. We include planning the action -again arbitrarily- in the cognition phase. The panels of Figure 2 illustrate the extension from a single task situation (left column) to a dual task situation (right column) for an active, reactive and passive BCI. Please note that the division in perception, cognition and action is useful in the current context because dual task situations can affect these phases separately, while the effects from one phase to the next are rather independent, for instance error rates or the distribution of errors are unaffected by earlier phases [7-9].

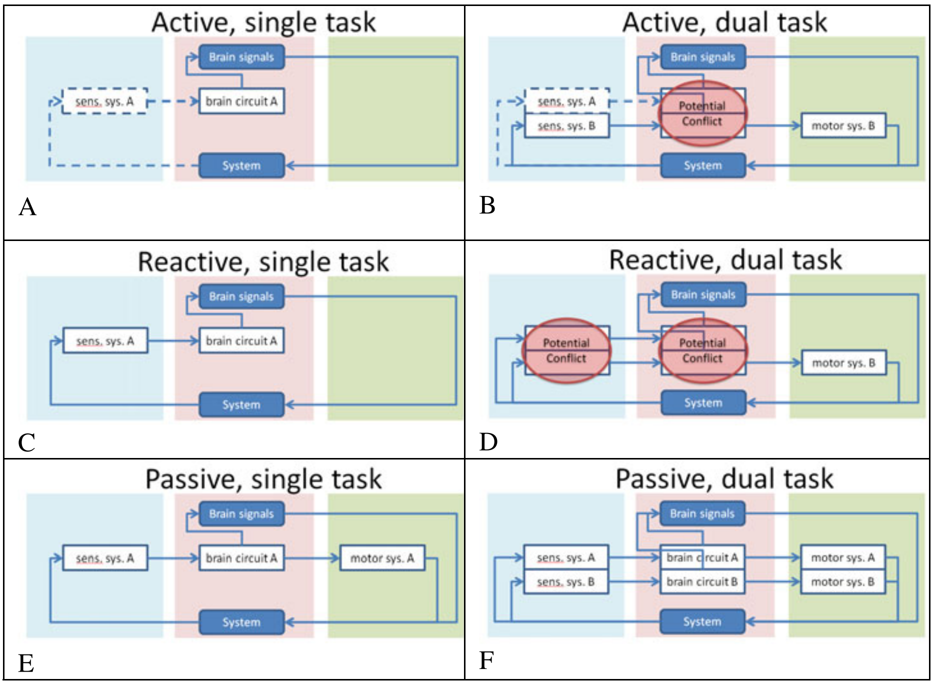

Fig.2. Extending the three BCI classes from a single task situation (left column) to a dual task situation (right column). The ovals indicate a potential conflict that may arise in BCI use in dual-task situations.

The classic BCI as described earlier can be considered as an active, single task BCI. The user performs task A (here task A is controlling the BCI) through employing brain circuit A (e.g. motor imagery). The acquired brain signals result in system changes that are (possibly) perceived by the user through sensory system A and there is no motor action step in this BCI (please note that for an (open-loop) active BCI, there is no strict requirement for a specific sensory system A – hence the dotted lines in panel A). For a second task B (BCI or non-BCI, cognitive or motor), the user may employ a brain circuit B, use motor system B to give the commands to the system and possibly perceive the results of this input through sensory system B. Panel B depicts the situation when we combine the active BCI with this task B. In this "active, dual task" situation, a conflict may rise at the level of the brain and the acquisition of brain signals which we will describe in more detail below. Panels 2C and 2D depict the situation for a reactive BCI. A reactive BCI uses the brain's reaction to specific probe stimuli. These probe stimuli rely on a specific sensory system A and the reaction to this probe stimulus in brain circuit A. As in panel A, there is no motor action involved in a single task, reactive BCI. Panel D depicts the situation for a task B added to the reactive BCI and shows that potential conflicts may arise at both the sensory system and the brain (e.g. because both may use the same sensory channel (e.g. visual) or brain process (e.g. attention). Finally, panels 2E and 2F depict the situation for a single and dual task passive BCI. Here, the BCI uses naturally occurring brain patterns when the user performs task A, and the same when the user performs tasks A and B. Of course, a conflict may occur when the user performs both tasks, but this will not affect the workings of the passive BCI. On the contrary, the goal of the BCI may even be the detection of such a conflict.

2.1 Psychological Models for Dual Task Situations and Coping with Conflicts

Here we briefly introduce Wickens' Multiple Resource Theory (MRT, e.g. see [10] for an overview) because this model provides relevant guidance on how to reduce dual task interference. The basic version of the MRT knows three independent dimensions, here given with their associated brain circuitry: a) stage of processing: perceptual and cognitive (posterior to the central sulcus) vs. selection and execution of action (anterior to the central sulcus); b) code of processing: spatial (right hemisphere) vs. verbal/linguistic (left hemisphere); and c) modality: auditory (auditory cortex), visual (visual cortex), and possibly tactile (somatosensory cortex). A large body of evidence confirms the assertion that the degree to which two tasks use different levels along each of the three dimensions reduces interference between the tasks. Several variants (e.g. [11]) and extensions to this basic MRT have been suggested in recent years. For instance Boles et al. extended the number of perceptual resources by distinguishing spatial positional, spatial quantitative and other resources (for recent work here, see [12]).

Applying a reactive BCI in a dual task environment can potentially lead to a conflict at the stage of the sensory system (perceptual processes) and the brain (higher order cognitive processes). At the sensory system, the probe stimuli required by a reactive BCI may interfere with sensory processing required for task B. This risk of sensory overload is relatively common in user-system interactions and several information processing models further detail the risks and possible solutions. A way to reduce the effects of a potential conflict is to employ different sensory systems for the probe stimuli of task A and the system feedback for task B (but see [13] for interference of concurrent stimulus processing). Although both may often be visual, the use of auditory and haptic displays increases [14]. Recent examples of using tactile stimuli as probes in a reactive BCI show that this is feasible and performance is comparable to that with visual stimuli [15, 16]. Interestingly, the use of multisensory stimuli in the context of BCIs is not widely used while this is a proven solutions in other domains.

A more complicated and challenging issue is the potential conflict that can arise at the level of the brain for active and reactive BCIs. There are actually two issues here. The first is similar to the sensory conflict described above: the tasks may use the same resources (brain circuits) and thus result in an overload situation (this is not different from two non-BCI tasks that use the same cognitive resources). The second is that even when tasks A and B use different and not-interfering brain circuits, the brain signals acquired by the BCI may still be affected by those of task B. This is inherent to most signal acquisition systems. For instance, the electrical signals acquired by EEG sensors have a low spatial specificity and not only represent activity of brain areas directly underlying the sensor but also areas centimetres away. Solving this issue is outside the scope of this paper and progress made in both sensor technology and computational algorithms may reduce this issue.

Coping with dual tasks that use the same cognitive resources (brain circuits) is an important challenge. Within the BCI domain, this challenge has also been tackled from a single task perspective, e.g. [17] provides a good overview. Dual task situations will further complicate the challenge. First, we must state that people are not very good at executing two tasks at the same time or in close succession [18], even though the brain seems to adjust to dual tasks situations (e.g., by dividing tasks among the left and right anterior prefrontal cortex compared to using both in a single task situation [19, 20]). However, some tasks interfere less with each other than others. A rule of thumb is that the more the two tasks share the same resources or brain circuits, the more they interfere. Although there is a large set of possible task combinations that has not been investigated yet, data indicating such competition are available for the more common combinations. For instance, working memory and visual search compete for the inferior and middle frontal cortex [21], manual tracking and visual detection seem to compete for the primary motor and somatosensory cortices involved with controlling the tracking-hand [22], manual tracking (driving) and listening affects the parietal lobe [23], and two motor tasks compete for the primary motor cortex [24]. Unfortunately, the literature is more keen on reporting tasks that do interfere than those that don't. Identifying two tasks that do not or only to a certain degree interfere and of which the brain circuits are spatially separated is an important challenge and must be based on neuroscientific as well as behavioural studies. A good point of departure are the dimensions of the MRT.

Another relevant aspect is that simply trying harder cannot overcome the limitations of a central cognitive bottleneck [25], but training may reduce the amount of interference. This training effect is not only visible in increased performance but also in the reduced overlap in employed brain circuits. For instance, Rémy et al. [26] investigated the combination of a bimanual task with a visual search task. After training of the manual task, the overlap between regions involved in both tasks was reduced, possibly due to automaticity of the manual task.

3 Combining BCIs

In this section, we will have a closer look at the consequences of combining different BCI classes. Please note that in the assistive technology domain, the term hybrid BCI was introduced to refer to combinations of BCIs or of a BCI with other control devices (e.g. [27]). In the user-system interaction domain, the common term is multimodal interface. Earlier work on this topic was restricted to either the serial use of two BCIs (e.g. one BCI serving as an on-off switch of a second BCI) or as redundant input channels in the same task [27, figure 1]. Here we focus on multi-task situations in which two BCIs are used (simultaneously) for two different tasks. Again, conflicts may be expected at the sensory system (when combining two reactive BCIs) and/or the involved brain circuits (when combining two active BCIs or an active and a reactive BCI). For combinations with a passive BCI, no conflicts are involved. Recent examples are the multimodal BCI described by [27] using event-related desynchronization and steady-state evoked potentials in a redundant set-up (i.e. both provide input to the same task and are integrated to provide the input to this single task) and [28] using (actively generated) alpha rhythm and SSVEPs.

Combining two active BCIs or an active and a reactive BCI may result in a conflict between the involved brain circuits. Combining two active BCIs is essentially a dual task and as such may suffer from the same effects described in the previous section, and choosing two appropriate tasks is essential. For instance, Sangals and Sommer [29] showed that a simple choice task with foot responses interferes with response preparation for a manual choice task. This indicates that two active BCIs based on motor (imagery) tasks may not be a good choice. The situation is even more complicated than a single active BCI in a dual task situation in the sense that the two brain circuits involved should not only be 'independent' of each other, but also spatially distributed or the sensor system may have difficulties in classifying the two tasks. The brain circuit conflict for combining an active and a reactive BCI is potentially less severe. In principle, performing a mental task and paying attention to probe stimuli can be combined. Since the 'attention wave' required by the reactive BCI will be located centrally, it is recommended to use a mental task for the active BCI that involves brain circuits located more lateral or frontal, or which signal is clearly distinct from the attention wave (e.g. based on spectral features).

When combining two reactive BCIs (i.e. each connected to a different task), it is strongly recommended to use two different sensory modalities to present the probe stimuli. But even then, it is doubtful whether the user is able to pay sufficient attention to targets in the two modalities to obtain a unique and measurable brain pattern. This is related to the fact that both BCIs will also compete for the same central brain circuits or resources as for instance shown for auditory and visual stimuli [30, 31]. Or in other words: the location of the relevant brain signal indicating whether attention was paid to a stimulus is more or less independent from the stimulus modality. For instance, Brouwer and colleagues [15, 16] investigated visual, tactile and bimodal visual/tactile probe stimuli and found only small differences in location of the P3 (i.e., the 'attention wave') as function of sensory modality. This means that exact time-locking of probe stimuli and EEG is critical and probe stimuli in both modalities should be out-of-phase. Another problem that may arise is the cost involved in switching attention between sensory modalities (e.g., in terms of required time [32, 33]). This means that for instance, using the two BCIs consecutively and not parallel may introduce a new bottleneck.

4 Integrating BCIs in a Multimodal User Interface: Relevant Issues

Especially in applications for healthy users, a BCI will not be a stand-alone interface between user and system but part of a multimodal user interface. Like other input and output modalities, integrating a BCI in a multimodal interface requires careful consideration of several aspects. Up till now, little or no attention in the design of BCI applications is given to usability related aspects such as comfort and ease of use). Here we will list several issues that are of particular relevance for BCIs, but we do like to stress that general guidelines with respect to interaction design should also be taken into account such as adjusting the interaction to the user, task and context of use characteristics (see ISO 9241 series on international usability standards).

- BCI as control device should be combined with a compatible display modality. Known compatible combinations in multimodal interfaces are for instance manual control – visual display, and vocal control – auditory display [34]. This is an important research topic for BCIs.
- The choice for a specific BCI category should be based on the task requirements and the strength and weaknesses of specific BCIs. As we coined the term modality appropriateness for the choice of display modality, we propose to use BCI appropriateness for this choice.
- A topic of specific interest is how to combine a (active or reactive) BCI with other control devices and prohibit interference [35].
- For passive BCIs, policies related to the fusion of BCI results with other physiological data must be developed.
- A specific BCI issue is the question of how to switch a BCI on and off. Since users cannot simply switch their brain activity on and off, specific solutions are required. One should also ensure that the current system interaction state is communicated to the user and that the system appropriately provides feedback when it initiates a modality change.
- In case the classification accuracy is limited, the system should confirm its interpretations of the user input (when appropriate after fusion and not for each modality in isolation). In this situation, users should have an option to choose alternative interaction modalities and be allowed to switch to a different modality.

5 Discussion and Preliminary Guidelines

We started by making an inventory of relevant issues when extending the use of different types of BCI from a single task environment to a multitask environment. Although we can build on the lessons learned from the user-system interaction domains and relevant information processing models such as the MRT, there is a need to get better insight in how to choose BCI modalities and tasks that only minimally interfere, i.e. they should be functionally and spatially separated. We expect that the identification of non-conflicting tasks will benefit from studies in high resolution brain imaging. A relevant addition of the MRT is linked to the sharing of task goals. For instance, tasks that would normally interfere like driving and listening will do so to a lesser degree when they share the same task goal, i.e. listening to navigation instructions. The same may hold for BCI tasks in a multitask environment. We also looked into the situation where BCI feedback or probe stimuli may lead to sensory overload or interference. The use of alternative sensory modalities or multisensory stimuli may reduce this risk, but the sensory modality should also be compatible with the BCI task. An important next step here is to have a quantitative evaluation of the identified conflicts.

Now that BCI technology is maturing and the range of possible applications expands, it is necessary to look more closely at general usability aspects. So far, usability does not seem to play the role it must when preparing BCIs for operational use outside the lab and for a growing range of users. This also means that the range of BCI paradigms should be stretched beyond the commonly used motor imagery for active BCIs and P3 matrix speller for reactive BCIs. Systematically looking into the task requirements and context of use can result in a better match of BCI as control device and other user-system interaction components. Having said that, we would also like to stress that BCI applications can still be considered embryonic and that many technological issues should be solved in hardware development, signal processing and system integration. Based on the issues we discussed and general user-system guidelines we formulate the following preliminary guidelines for BCI design and multimodal interaction:

- A BCI should be used if it improves satisfaction, efficiency, or other aspects of performance for a given user, task and context of use.
- The BCI category should match the task requirement.
- The BCI coding should match the task requirements (e.g. letters for a spelling device and directions for a navigation task).
- The feedback to the user or the BCI probe stimuli should match the BCI coding and presented in the appropriate sensory modality (e.g. letters visually, directions through spatial audio).
- The feedback to the user should match with the strengths, weaknesses and possibilities of the BCI and not go beyond its capabilities.
- Ensure that the display modalities are well synchronized temporally as well as spatially.
- Minimise possible interference between the BCI task and other tasks, both functionally and in relation to the spatial specificity of the BCI acquisition system.
- Aim to combine tasks that share the same task goals.
- Minimise possible interference between the sensory system involved in the BCI and other user-system interaction components.
- Performing tasks sequentially instead of simultaneously may reduce sensory or cognitive conflicts but may also involve costs of task and/or modality switching.

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