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Collaborative Project of the 7th Framework Programme

Work Package 3
Multimodal sensing and monitoring system for BNCI, affective and biometric signals

D 3.1: State of the Art Analysis: BCI and BNCI Systems

Graz University of Technology
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Document Information

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Abstract (for dissemination)	This deliverable requires one article ready for submission to a peer-reviewed journal or book. We instead present five articles that have already been submitted to peer-reviewed journals and books. The main BCI review article (Graimann, Allison, and Pfurtscheller) accomplishes most needs of this deliverable – a review of BCI and BNCI systems. Other articles further address the deliverable by providing additional information.
Keywords	BCI, BNCI, neuroprosthetics, EEG, hybrid, P300, SSVEP, ERD

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Issue Date	**Version**	**Author**	**Change**
19 Apr 2010	0.1	Allison	Initial document created
21 Apr 2010	0.2	+ Faller	Revised TOC, figure captions, formatting
21 Jun 2010	0.3	+ Faller + Scherer	Reference updates, final review, formatting
24 Jun 2010	0.4	+ Faller	Formatting
28 Jun 2010	1.0	+ PMO	Last formatting, final version released to the P.O.

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1 Summary

1.1 Status of Deliverable: Completed

D3.1 requires a review and analysis of the state of the art in BCI and BNCI systems. This must be ready for publication in a peer reviewed journal or book by M6 (June 2010). We have completed this deliverable ahead of schedule, and have exceeded the requirement by producing not one article but five articles that address the deliverable specification. Section 2 presents the five articles and their publication status. In this section and the remainder of this document, authors who are employed with BrainAble are highlighted in **boldface**. All five articles acknowledge BrainAble, including the project number.

Section 2 below describes how each of these five articles addresses the specific text relating to the deliverable requirement. Generally, each of the requirements is addressed by more than one article. There is one minor exception: none of the deliverables explicitly discusses relevance to BrainAble, so this relevance is summarized at the end of this report. Section 3 presents the current status of each article, and copies of each article will be attached to the deliverable report, as noted in Annex 1.

1.2 Relevant text from DoW

The text below is copied from the DoW. This deliverable text refers to both D3.1 and D3.2. This report is concerned only with D3.1, which is defined in the DoW as:

D.3.1. State of the Art Analysis: BCI and BNCI systems (M6, Report, Public)[1].

D3.2 is focused on details of sensors, signals, and signal processing. These topics are briefly overviewed in 3.1 as well.

Task 3.1: Two updated State of the art analyses: one for multimodal sensing devices, and another one for BCI systems.

(Task Leader: TU-GRAZ. Other partners involved: G.TEC, UPF)
One of the a priori needs in this proposal is a thorough knowledge of the very latest progress in multimodal sensor systems *and the BCI systems that use them*. This knowledge is also important in a cluster project, Future BCI, which requires a review of "sensors, signals, and signal processing" and a review of BCI systems, and thus BrainAble and Future BCI will remain abreast of each other's work.

TU-GRAZ will coordinate one peer-reviewed journal article, which will be an updated review of BCI/BNCI systems, including different signal types and issues relating to BNCI systems that combine direct information from the brain and other signals. TU-GRAZ and G.TEC will coordinate a second article that will review sensors, signals, and signal processing relevant to BNCI systems. These two articles will reference each other and could serve as good companion articles to each other. Readers of the BCI/BNCI review who wish more details of

[1] In the text below, key text that relates to D3.1 is *written in italics*;

sensors, signals, and signal processing can read the second review. Readers of the second review who would like to learn more about other components of BCIs and BNCIs can read the first article. *Emphasis will be on actionable, real world developments rather than theoretical discourse or "blue sky" future possibilities. Both reviews will be ready for submission to a peer-reviewed journal or book in M6. The work will be subdivided as follows:*

***TU-GRAZ:** TUG will be primarily responsible for the "BCI/BNCI" review. The article will include EEG BNCI for control (aka BCI): overview, types, components, applications, user groups, and relevance to BrainAble. Devices to monitor affect will be briefly overviewed as well.*

G.TEC and TU-GRAZ: These partners will be jointly responsible for the "sensors, signals, and signal processing" review article. The article will include hardware and software issues for BNCI (EEG, HR, and other signals) and signal processing issues relevant to these signal types.

UPF: Sensing CNS activity via peripheral signals such as Electro Dermal Activity (EDA) and respiration to assess affective responses in virtual scenarios, especially for self-expression and training.

Technical quality can be assessed through the thoroughness, accuracy, and relevance of the review. The review can also be judged by its medium. That is, if the review is accepted to an established journal or book, with a solid reputation and high impact factor, then the review was considered of high quality by the objective reviewers of that medium.

The requirement to emphasize real-world developments is not addressed below, because all five articles do this. All five articles focus on recent developments, highlighting recent article citations and new progress, and address real-world issues.

Please note that the term "BNCI" has never been officially defined anywhere (source: three different project officers or more senior persons working in ICT in the EC). It seems that BNCIs are meant to be a supercategory of BCIs because BNCIs can also use devices from peripheral signals as well. Indeed, another EC funded project, the Future BNCI project, is expected to define BNCIs by June 2011. For now, this deliverable assumes the "working definition" of BNCI: a BCI that can also rely on signals from the peripheral nervous system.

2 How we met the requirements of D3.1

Section 2 describes how these five articles address the DoW text that is highlighted in yellow above. The requirement to emphasize real-world developments is not addressed below, because all five articles do this. All five articles focus on recent developments, highlighting recent article citations and new progress, and address real-world issues. The relevance to BrainAble is discussed in only one article (Allison, in press), and hence is further expanded in part 2.6. The discussion of technical quality is addressed in part 2.7.

Each of the five following Sections (2.1-2.5) summarizes one article, then discusses how the article meets the text in the DoW. One figure from each article is also included; please see the original text for more descriptive captions and descriptions.

2.1 Graimann, **Allison,** and Pfurtscheller (in press)

This article reviews BCI and BNCI systems. It was developed as the introductory chapter to a book that is edited by Graimann, Allison, and Pfurtscheller. This book is intended for non-expert readers. Therefore, all chapters (including this introductory chapter) are written in a straightforward way, without excessive terminology or technical details.

"TU-GRAZ will coordinate one peer-reviewed journal article, which will be an updated review of BCI/BNCI systems, including different signal types and issues relating to BNCI systems that combine direct information from the brain and other signals."

This article is an updated review of BCI and BNCI systems. The article solidly reviews different types of BCIs and discusses BNCIs with considerable discussion of neuroprosthetic BNCI systems (figure 2 also summarizes BCI and BNCIs). Although the text in the DoW says the article will be a journal article, we assume that a peer-reviewed book chapter is also acceptable. Moreover, the text later in the WP3 description says it will be a journal or book.

"TUG will be primarily responsible for the "BCI/BNCI" review. The article will include EEG BNCI for control (aka BCI): overview, types, components, applications, user groups, and relevance to BrainAble. Devices to monitor affect will be briefly overviewed as well."

This article addresses all of these, except it does not mention relevance to BrainAble (please see part 2.6 below). Section 1 is an overview of BCIs. Sections 1.1 and 1.2 discuss different components. Section 1.2 discusses the different types of invasive and non-invasive BCIs, and also discusses major terms like synchronous and asynchronous. Section 1.4 describes applications of BCI and BNCI systems.

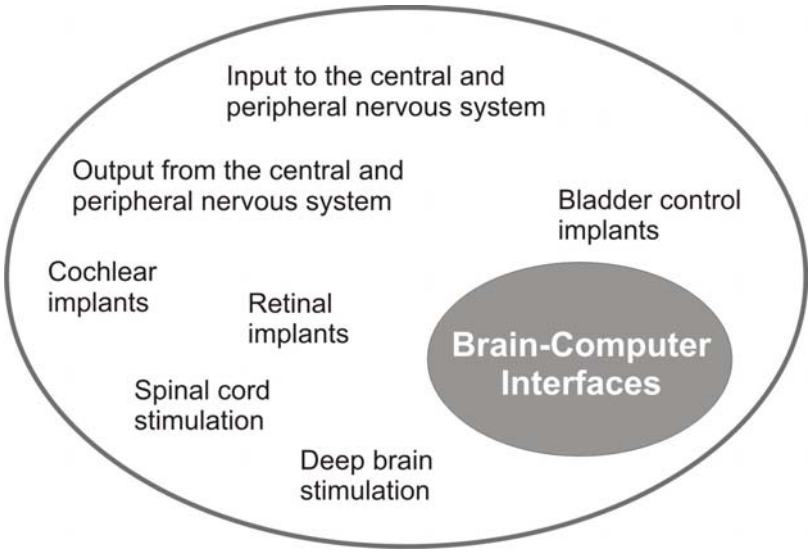

Figure 1: This image is Figure 2 from Graimann et al. (in press). It summarizes BCI systems in relation to other BNCI systems.

2.2 Allison (in press)

This article briefly reviews BCIs and BNCIs and discusses issues regarding the mechanics of change in the near future. It was developed as the concluding chapter to a book that is edited by Graimann, Allison, and Pfurtscheller. As noted above, this book is intended for non-expert readers, and hence is written at an appropriate level.

"TU-GRAZ will coordinate one peer-reviewed journal article, which will be an updated review of BCI/BNCI systems, including different signal types and issues relating to BNCI systems that combine direct information from the brain and other signals."

This article does briefly review these issues, but in less detail than Graimann et al. (in press).

"TUG will be primarily responsible for the "BCI/BNCI" review. The article will include EEG BNCI for control (aka BCI): overview, types, components, applications, user groups, and relevance to BrainAble. Devices to monitor affect will be briefly overviewed as well."

This article addresses all of these. Again, the emphasis is more on real-world developments in the near future rather than other time frames. The article explicitly discusses future directions with hybrid BCIs, alternate signals used in BNCIs, affective monitoring (monitoring fatigue and other states), new applications (prominent in Section 2) and user groups (especially Sections 3.2 and 3.3), and different types and components of BCIs.

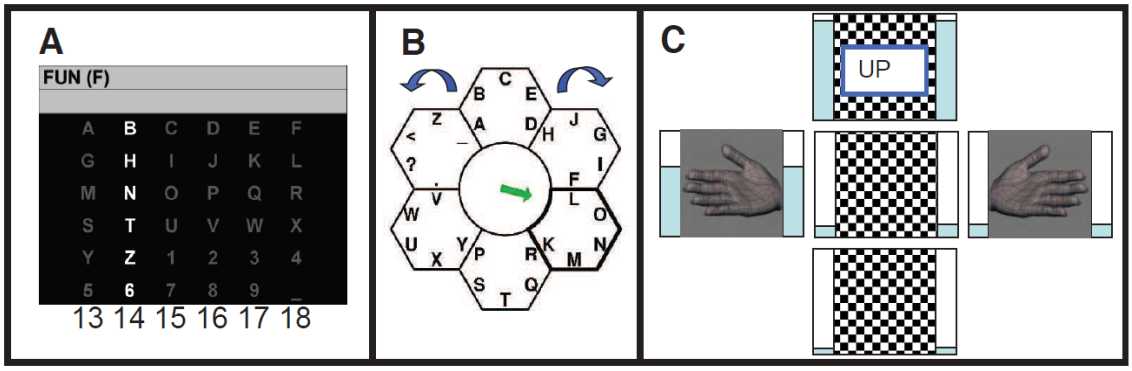

Figure 2: This image is Figure 2 from Allison (in press). It describes three different potential hybrid BCIs, which could be adapted to BrainAble. The middle image in Panel B shows a variant on Hex-O-Spell, which is the basis for the Hex-O-Select system that will serve as the central interface in BrainAble. The text near this figure explicitly mentions Hex-O-Select.

2.3 Pfurtscheller et al. (2010)

This article briefly reviews hybrid BCIs – BCIs that are combined with other communication systems, including other BCIs.

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This article is not a general review of all BNCIs. It reviews hybrid BCIs, some of which include other physiological signals (and are therefore BNCIs).

"TUG will be primarily responsible for the "BCI/BNCI" review. The article will include EEG BNCI for control (aka BCI): overview, types, components, applications, user groups, and relevance to BrainAble. Devices to monitor affect will be briefly overviewed as well."

The article does address all of these, but in less detail than other work, and with an emphasis on hybrid BCIs. The work discusses BCIs based on EEG and NIRS, and BNCIs based on breathing, eye tracking, and HR.

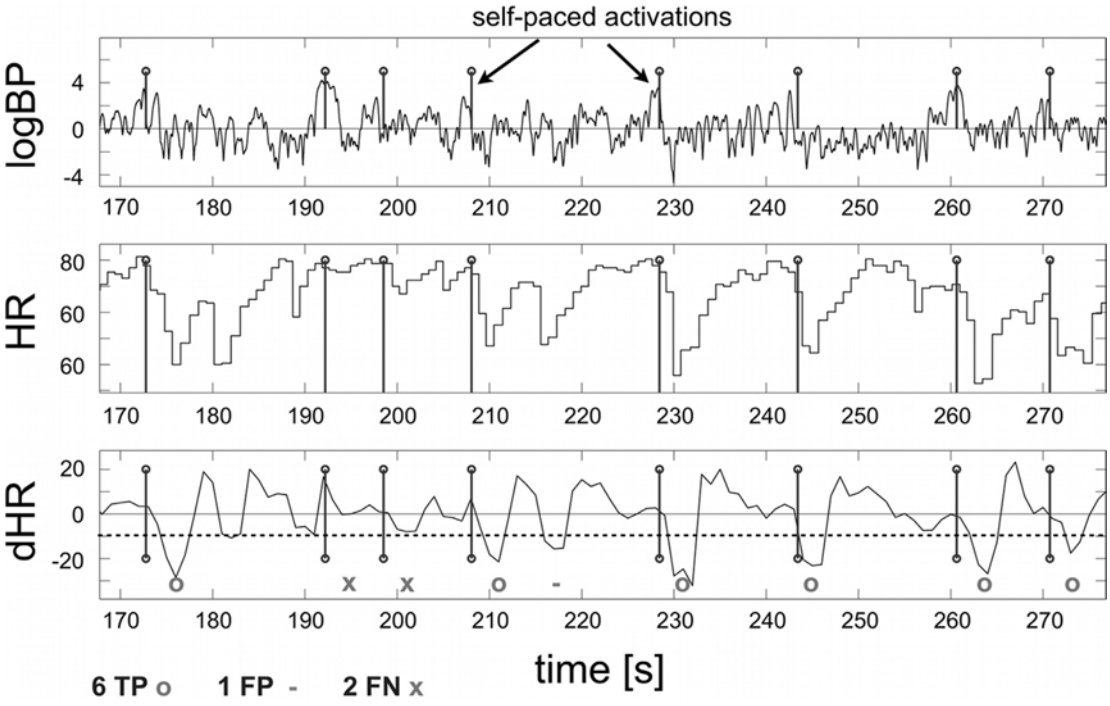

Figure 3: This image is Figure 6 from Pfurtscheller et al. (in press). It shows activity from the EEG (a BCI) and heart rate (a BNCI) as people performed motor imagery. Results could be used in a BrainAble hybrid BCI that uses both of these signals.

2.4 Allison and Neuper (in press)

This article addresses a major challenge in BCI research: BCI illiteracy. This refers to the fact that some people cannot use some BCIs.

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The article focuses primarily on EEG BCIs, though the article notes that comments could apply to similar systems as well.

"TUG will be primarily responsible for the "BCI/BNCI" review. The article will include EEG BNCI for control (aka BCI): overview, types, components, applications, user groups, and relevance to BrainAble. Devices to monitor affect will be briefly overviewed as well."

The article focuses only on EEG BNCI for control (aka BCI). It discusses the three major types of EEG BCIs (P300, ERD, SSVEP) and the different components. There is no significant discussion of the applications, user groups, relevance to BrainAble, or monitoring affect.

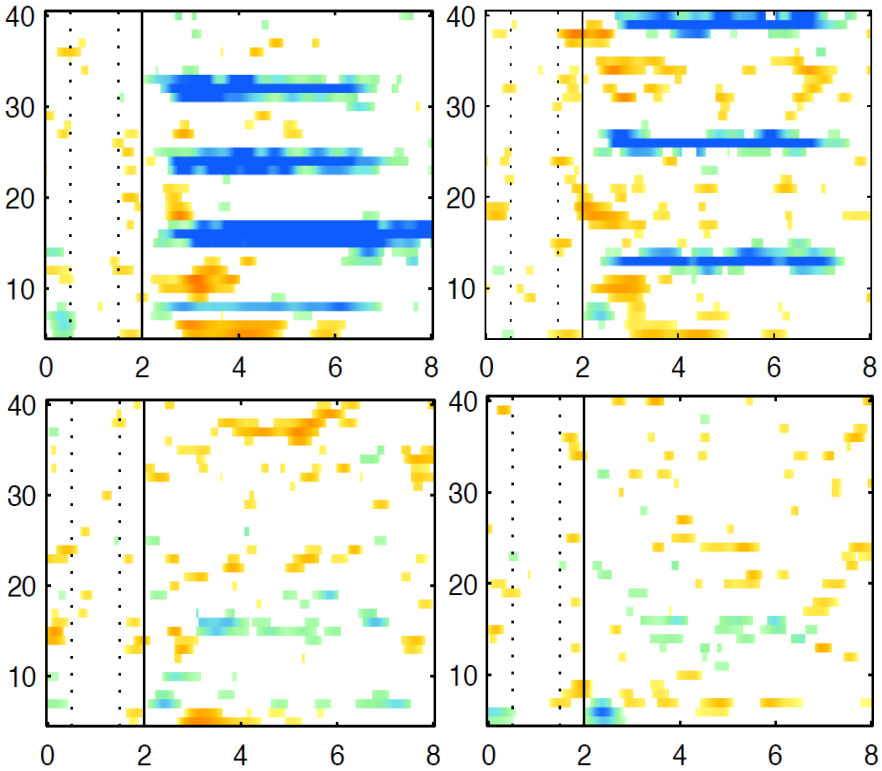

Figure 4: This image is Figure 3 from Allison and Neuper (in press). The top two panels show a subject who had very clear signals in an SSVEP BCI (shown by the horizontal blue lines). The bottom panels show a subject who performed the same task, but did not produce clear signals. Hence, the top subject could use an SSVEP BCI, but the bottom subject could not. BrainAble (and any BCI project) should address this phenomenon of "BCI illiteracy."

2.5 Neuper and Allison (in revision)

This article focuses on neurofeedback principles and how they relate to BCI research. The article emphasizes that much of BCI learning occurs through neurofeedback, but that fundamental neurofeedback principles are often ignored when developing BCIs

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The article focuses primarily on EEG BCIs, though the article notes that comments could apply to similar systems as well. The article also discusses HR changes during BCI use.

"TUG will be primarily responsible for the "BCI/BNCI" review. The article will include EEG BNCI for control (aka BCI): overview, types, components, applications, user groups, and relevance to BrainAble. Devices to monitor affect will be briefly overviewed as well."

The article focuses on EEG BCIs. The article includes an overview of BCIs, and discusses types of BCIs and how feedback differs for different types of BCIs. Figure 1 and the associated text describe different BCI components. Different parts of the text describe different applications, particularly applications in virtual environments. For example, as noted above, Figure 6 describes how EEG and HR activity change when someone uses a BCI in a boring environment vs. an environment with rich visual feedback. There is no strong discussion of different user groups and relevance to BrainAble.

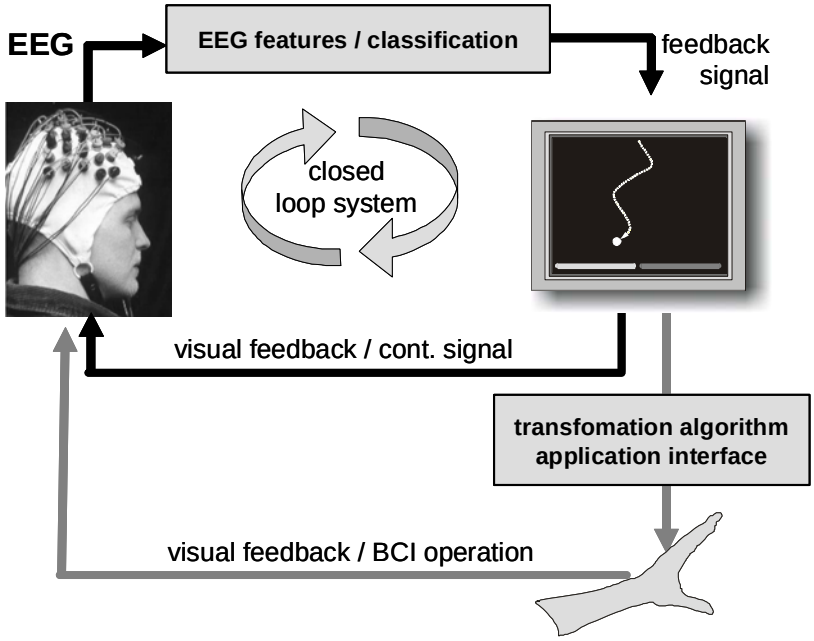

Figure 5: This image is Figure 1 from Neuper and Allison (in review). It presents the different components of any BCI. Any BCI requires four components: signal acquisition, signal classification, output (such as device operation and feedback), and an application interface (aka operating system).

2.6 Relevance to BrainAble

The Graimann et al. (in press) and Allison (in press) articles are both very relevant to BrainAble. These articles review and discuss BCIs and BNCIs. The first article is the main review article, with relatively little commentary. The relevance to BrainAble is obvious in many ways – for example, BrainAble emphasizes different types of BCIs, which this article discusses. The latter article is longer, with more commentary and less review. It addresses many topics that BrainAble expects to consider, such as integrating BCIs with devices based on other signals, hybrid BCIs, practical home use, improved interfaces, the Hex-O-Select system we plan to use as a Universal Application Interface (UAI), etc.

The Pfurtscheller et al. (in press) article focuses on hybrid BCIs. It discusses hybrid BCIs that combine BCIs with other BCIs, and hybrid BCIs that combine BCIs with BNCIs that monitor other physiological signals, such as activity based on eye movement, breathing, or HR. Both of these types of hybrid BCIs are relevant to BrainAble. The article also discusses BCI and BNCI systems in virtual reality.

BrainAble states that one way to assess performance is by illiteracy – the number of users who cannot use a BCI. Allison and Neuper (in press) focuses on illiteracy and how to reduce it, with attention to distinct issues for each of the BCI types. These comments could be helpful throughout BrainAble.

Neuper and Allison (in revision) addresses another major issue in any BCI: neurofeedback. BrainAble also plans to develop graphically rich, engaging feedback environments, and hence this article is helpful. BrainAble also heavily emphasizes virtual reality and mixed reality feedback, which is discussed in this article.

2.7 Evaluation

Technical quality can be assessed through the thoroughness, accuracy, and relevance of the review. The review can also be judged by its medium. That is, if the review is accepted to an established journal or book, with a solid reputation and high impact factor, then the review was considered of high quality by the objective reviewers of that medium.

The thoroughness, accuracy, and relevance of the review should now be apparent. Indeed, there was not simply one review submitted for this deliverable. One article (Graimann et al. In press) focuses on reviewing BCIs and BNCIs, while the other four articles review elements of BCIs and BNCIs and include additional commentary. The preceding material in Section 2, and the substance of these articles, should clearly convey that this deliverable has been addressed in a thorough, accurate, and fair fashion.

All five articles were reviewed by critical BCI experts, then accepted to established journals or books through great publishers. Graimann et al. (in press) and Allison (in press) will be published by Springer Berlin, and Allison and Neuper (in press) will be published by Springer London. Pfurtscheller et al. (in press) will appear in Frontiers in Neuroprosthetics, a solid journal that will publish a lot of BCI work in the near future. Neuper and Allison (in revision) will be published by Cambridge University Press, another solid publisher.

3 Status of the five articles

All five articles have been accepted for publication.

Graimann et al. (in press) and Allison (in press): These articles were accepted by the editors in early April 2010 and sent to the publisher, Springer, in late April 2010.

Pfurtscheller et al. (2010): This article was published online in April 2010

Allison and Neuper (in press): The proofs of this article are expected from the publisher in June.

Neuper and Allison (in revision): This article was accepted for publication, but the authors may be asked to make minor edits.

References

- Graimann, B., **Allison, B.Z.,** and Pfurtscheller, G. An introduction to brain – computer interface (BCI) systems, In: *Brain-Computer Interfaces: Revolutionizing Human-Computer Interaction*, editors: Graimann, B., Allison, B.Z., & Pfurtscheller, G. Springer. (in press).

- **Allison, B.Z**. Toward ubiquitous BCIs. In: *Brain-computer interfaces: Revolutionizing Human-Computer Interaction*, editors: Graimann, B., Allison, B.Z., & Pfurtscheller, G. Springer. (in press).

- Pfurtscheller, G., **Allison, B.Z.,** Brunner, C., Bauernfeind, G., Solis Escalante, T., **Scherer, R.,** Zander, T.O., Müller-Putz, G., **Neuper, C**. and Birbaumer, N. (2010) The hybrid BCI. *Frontiers in Neuroscience,* 4:42. doi:10.3389/fnpro.2010.00003.

- **Allison, B.Z.** and **Neuper, C**. Could anyone use a BCI? In: *(B+H)CI: The Human in Brain-Computer Interfaces and the Brain in Human-Computer Interaction,* editors: Tan, D.S. and Nijholt, A. Springer. (in press).

- **Neuper, C.** and **Allison, B.Z**. Neurofeedback Principles in BCI Research. In: *Different psychological perspectives on cognitive processes: current research trends in Alps-Adria region,* Actis, R. and Galmonte, A. (Eds.), Cambridge University Press. (in revision).

Annex 1 – Content of the five articles

Please see the five attached files, which contain the five articles described here.

The Pfurtscheller et al. (2010) article is also available through standard library search engines. The remaining four articles will be published in books that will be available after this deliverable report is complete. Hence, they are not publicly available now, but this should change soon.