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EVALUATION OF BCI RESEARCHERS' OPINIONS REGARDING THE FUTURE OF BCIS: RESULTS OF BCI ROADMAP QUESTIONNAIRE 2014

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ABSTRACT: The field of Brain-Computer Interface (BCI) research has seen a steep expansion during the last years, and interesting progress has been made in all different aspects of the BCI pipeline. Despite that, BCIs are not yet widely used by either the diseased or healthy target populations. In the current study, we asked BCI researchers worldwide to fill out a questionnaire about how they see the future of BCI research, what hurdles need to be taken for BCIs to become available and widely used applications, and the research that is needed to accomplish this. The data reveal that researchers foresee that real BCI applications will appear on the market in the coming years, but that important improvements are needed in especially the hardware, performance and user friendliness of BCIs.

INTRODUCTION

Since the pioneering work on brain-computer interfaces (BCIs) in the late sixties and early seventies of the previous century [1,2], BCI research has seen a fast growth. The new insights gained as a result of that have led to the BCI field currently recognizing several types of application scenarios, each with their own target populations [3,4], ranging from applications to *replace* lost brain function (e.g. BCI-control of communication devices) to tools that *enhance* the daily functioning of healthy people (e.g. BCI-driven detection of attention lapses for airline pilots). Despite these developments, BCIs seem to remain largely a laboratory tool and are hardly available on the market. As a result, only a very limited number of patients and healthy people use BCIs in home, work or clinical settings.

In order to make sure that potential end-users, in time, will start to benefit from BCIs, it is important to identify the most promising BCI applications and target groups, and to signal topics that need more attention. To this purpose, a group of European BCI stakeholders (i.e. the BNCI Horizon2020 project, funded within the European Commission's Framework Programme 7) worked on the development of a roadmap for the BCI field [5], between November 2013 and May 2015. As part of this project, the consortium approached BCI researchers worldwide with the request to fill out a questionnaire, asking them about their view on the current status and the future of their field. A summary of the findings was presented in one of the Appendices of the BNCI Horizon2020 roadmap. Here, we present the results of the questionnaire in more detail.

MATERALS AND METHODS

Approach: In May 2014, the BCI researchers' questionnaire was sent to 3291 BCI researchers by email, followed by two reminders to non-responding researchers before the first round was closed in July 2014. A second round ran from December 2014 until January 2015.

Questionnaire: The questionnaire contained three sections:

1) Respondents. Here, researchers were asked to answer a list of multiple choice questions on e.g. their education, lab size, and BCI research focus, with the purpose to characterize the respondents.
2) Near future. In this section, researchers were asked to shortly describe a BCI application that they considered feasible within the near future, and assign it to one of the BCI scenarios (*replace, restore, enhance, improve, supplement and research tool*). Then, they were presented with a list of potential bottlenecks and a list of possible research directions. For each item, they had to indicate to what extent it applied to the BCI application they just described, on a five-point rating scale that ranged from strongly agree to strongly disagree.
3) Far future. Here, respondents were asked to think out of the box and into the far future, and shortly describe a potential killer application or major research breakthrough, for both non-invasive and implanted BCIs.

Data analysis: Data analysis was performed separately for each section.

1) Respondents. Numbers of selections of multiple choice items were computed as percentages of the total number of respondents.
2) Near future. The described BCI applications were evaluated for clarity and correctness of assignment to the application scenarios and re-assigned if necessary. Ratings were labeled with weights, i.e. 'not applicable' with 0, 'totally disagree' with 1, 'disagree' with 2, 'neutral' with 3, 'agree' with 4, and 'totally agree' with 5. Subsequently, the ratings given by the respondents to each of the

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bottlenecks/research direction statements were used to compute, per statement, a center of mass (COM). COM values >3.5 indicated that most respondents agreed/strongly agreed with a statement, whereas COM values <2.5 indicated disagreement or strong disagreement. Values between 2.5 and 3.5 indicated not particularly relevant or irrelevant.

3) Far future. Incomplete and unclear answers were excluded from analysis. The other statements were used to assemble a list of numbered codes (topics). The final list covered all issues described by the respondents. Subsequently, each statement was annotated with one or more codes of the list. Finally, for each code, the number of instances among all statements on non-invasive and implanted BCIs was counted.

RESULTS

Respondents: In total, the questionnaire was filled out by 298 respondents, mostly from Europe, North-America and Asia. Almost 90% of them worked with non-invasive BCIs, the rest on implantable BCIs. The percentage of respondents working on implantable BCIs in North-America (26%) was substantially larger than in Europe and Asia (both < 10%).

Near future: The 298 respondents described and rated 363 BCI applications, of which 317 were included in the analysis. Most of the applications were related to *replacing* lost central nervous system (CNS) output, followed by tools to *improve* lost CNS output (Table 1). Over 80% of the applications were suggested to be developed using a non-invasive BCI approach.

Bottleneck statements that respondents considered most relevant for their non-invasive applications were those related to insufficient system performance (COM>3.5 for 6 out of 6 BCI scenarios, i.e. *replace, restore, enhance, improve, supplement* and *research tool*), the unawareness of end-users about BCIs (COM>3.5 for 5/6 scenarios), the complexity of BCI systems (COM>3.5 for 5/6 scenarios), and the fact that wishes and needs of end-users are not met sufficiently (COM>3.5 for 4/6 scenarios).

Table 1: Number of respondents describing an implanted and non-invasive solution for applications within the six BCI scenarios in the Near future section.

Scenario	Implanted	Non-invasive	Total
Replace	21	83	104 (33%)
Restore	6	11	17 (5%)
Improve	9	75	84 (26%)
Enhance	3	47	50 (16%)
Research	4	19	23 (7%)
Supplement	1	38	39 (12%)
Total	44 (14%)	273 (86%)	317

For *replace* applications with an implanted BCI approach, respondents agreed (COM>3.5) that durability and performance are insufficient, and that there is insufficient evidence of system performance, durability and the risk/benefit ratio for end-users. Also here, respondents agreed that end-users are insufficiently aware of BCIs.

Research directions considered most relevant for non-invasive applications were related to sensors and signal processing techniques to improve system performance, clinical trials to demonstrate system performance and identification of the wishes and needs of end-users. For implanted BCIs to *replace* CNS function, all research directions of the list received a COM rating of more than 3.5, indicating agreement/strong agreement with each of these.

Far future: In total, 169 and 178 far future statements, for non-invasive and implanted BCIs respectively, were included in the analysis. Statements were used to define a list of topics, and were subsequently labelled according to this list. Each statement received one or more label. Topics most often addressed in the statements were ‘user friendliness’ and ‘hardware: sensors’. Both these topics occurred most often in the non-invasive out-of-the-box statements. For implanted BCI out-of-the-box statements, ‘communication and environmental control for patients’ and ‘prostheses and artificial limbs for patients’ were referred to most often. In addition, ‘accuracy and reliability of signal processing and decoding’ was often addressed.

DISCUSSION

Here, we describe the view of BCI researchers about the future of their field, as determined by the responses to the BCI researcher’s questionnaire. Most respondents of the questionnaire worked on non-invasive approaches, which may not be surprising because of the practical difficulties associated with implanted BCI research, such as the limited number of available subjects and the access to the required medical context. Interestingly, our data showed a difference between North-America and Europe/Asia in the balance between non-invasive and implanted BCI research, which has been described before [6], and which may be related to a different perception or different regulations regarding implants. The percentages of researchers working on non-invasive (89%) and implanted (11%) BCIs corresponded largely with the percentages of applications using these respective approaches (86% vs 14%) that were described in the Near future section. This indicates that the opinion of the respondents about the bottlenecks and requirements for future research is based on actual expertise and knowledge of these issues, which subscribes to the validity of the results of this questionnaire.

There was quite some consistency about the bottlenecks and research directions that were considered relevant for the six non-invasive BCI application scenarios. One of the most important hurdles seems to be system performance. In fact, for 75% of the described non-

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invasive applications, the respective respondent indicated that (long-term) system performance is not yet good enough. Moreover, system complexity and the insufficient incorporation of the needs and wishes of end users needs to be addressed. Also for implanted BCIs to replace CNS function, system performance, as well as durability, needs to be improved. Moreover, respondents indicated that more data on performance, durability and the risk-benefit ratio are needed.

Interestingly, for both non-invasive and implanted BCI application descriptions, respondents indicated that potential users are unaware of BCIs. This finding does not agree with other studies involving healthy and disabled end-users, which showed that 50-80% of the interviewed potential end-users were aware of BCIs [7-9]. Whether this discrepancy reflects an inclusion bias of the respective studies, or whether our respondents underestimated the BCI-awareness of potential end-users remains to be determined.

When BCI researchers were asked to think out of the box and into the far future, and describe a killer application or major research breakthrough within the non-invasive BCI field, they most often referred to 'user-friendliness', indicating that systems have to become easy-to-use (in any environment), as well as wearable and durable. It is unlikely that the respondents of the questionnaire considered implanted BCIs more user-friendly than their non-invasive counterparts. Rather, the stage of the implanted BCI research field may be viewed as too premature to consider user-friendliness. Most out-of-the-box statements on implanted BCIs referred to *replacing* lost CNS function, indicating that a major breakthrough is needed to apply neuroscientific knowledge into actual BCI applications for patients.

Limitations of the current study include the limited number of respondents, which may be caused by the length and the relative complexity of the questionnaire, and a potential bias towards European BCI researchers. Despite that, several of our results correspond to previous reports, suggesting that the outcome of this questionnaire and the identified topics reasonably reflect the view of the BCI research field.

CONCLUSION

We conclude that BCI researchers are quite optimistic about the feasibility of BCIs becoming real and available applications for patients and healthy end users. However, more research is needed to solve several crucial issues related to hardware, performance and user friendliness before these products adequately meet the wishes and needs of the end-users and can eventually penetrate the market.

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