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# The P300 BCI: on its way to end-users?

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ABSTRACT: Looking at the past 30 years of research into the so-called P300 BCI reveals an almost exponential growth of publications on this topic as indexed in Pubmed. The striking increase has started around 2010 and is currently plateauing at a high rate. Certain aspects of the P300, such as stimulus presentation, feedback modality, classification procedures, or application to be controlled have been intensively investigated. The bulk of studies comprises one session approaches in the laboratory environment with healthy subjects, but patient end-users are increasingly included in studies. However, a lack of long-term studies with end-users in the field is obvious and indicates a translational gap. On the basis of more than 300 studies included, we discuss reasons for this gap and propose remedies; however, this paper presents a coarse overview only and constitutes the basis for a thorough meta-analysis.

## INTRODUCTION

The motivation for this overview arose from the observation that a strikingly high amount of manuscripts to be reviewed by the authors do not sufficiently take into account and build upon existing results within the field of the P300 BCI.

The foundations of the P300 BCI were laid with the first description of the P300 by [1] – an event-related potential that could be elicited in a so-called oddball paradigm with rare target and frequent standard stimuli. In 1988 Farwell and Donchin [2] implemented the oddball paradigm in a stimulation set-up to control a BCI. Letters and numbers were presented in a matrix on a monitor. Rows and columns of the matrix were flashed in random order and participants were required to focus attention on the letter to be selected. Focusing of attention was reinforced by asking the participants to count how often the target letter flashed. By this procedure, each letter to be selected becomes a rare target in comparison to all other letters, which turn into standard stimuli. Ever since, this paradigm has been adopted, adapted, changed, and extended in many ways, and reliable target selection in healthy subjects and patients with disease alike has been demonstrated in a plethora of studies. The primary aim of the P300 BCI has been communication and control to replace lost function in patients with severe motor impairment. Only recently have other aspects, such as for rehabilitation after post-stroke aphasia, i.e. to improve lost function (see the BNCI Horizon 2020 website for a categorization of BCI according to their application purpose), gained more attention [e.g., 3].

Despite the many studies aiming at improving different aspects of the P300 BCI such as accuracy, information transfer rate (ITR), or usability, P300 BCIs are not used in daily life by the targeted end-users with disease albeit most studies claim this to be the final goal and motivation for the experiment at hand.

Thus, we face two gaps: (1) a translational gap, which prevents the many positive results arriving at the end-users' home and (2) an awareness gap, i.e. researchers sub-optimally build on the results achieved by the community. Therefore, approaches to the P300-BCI and controlled applications remain idiosyncratic rather than evoking a joint effort toward bridging the translational gap.

In the following we will give a brief overview of the topics covered by P300 BCI related publications (Table 1) and then discuss questions and answers which we consider relevant for the field of the P300 BCI. Those may partially transfer to BCIs with other input signals.

## MATERIALS AND METHODS

We used Pubmed as source for our literature search on the P300 BCI. We entered the search terms "Brain" AND "Computer" AND "Interface". This search yielded n=733 hits. Those were then screened for true P300 BCI content and studies in languages other than English were excluded (n=12). Based on the abstracts, studies were then categorized according to the participants included (healthy subjects vs. participants with disease), environment of data collection (laboratory vs. field), number of (daily) sessions (one vs. more than one). Other categories were: "use of existing data sets", "reviews", and "theory and frameworks". During the process of categorization, the category "sample unclear" had to be created because it could not always be derived from the abstract what kind of sample was included.

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RESULTS

A sample of n=366 studies were included for analysis. Figure 1 depicts the number of publications per year. A gap of 12 years is visible between Farwell and Donchin's and subsequent papers. Thus, the next papers follow in 2000. By 2004 the number of publications per year was slowly increasing. Since 2011 it has reached a plateau of around 45 papers per year

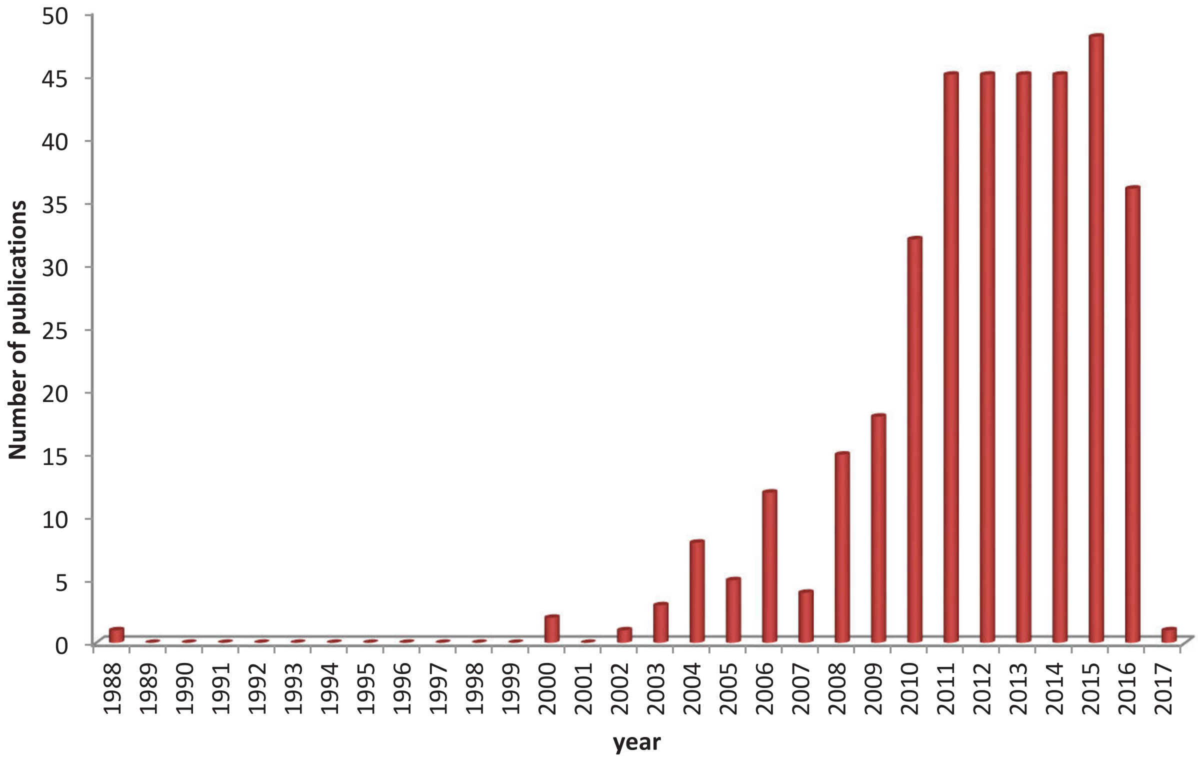


Figure 1: Number of P300 BCI related publications per year. Note, the gap between 1988 and 2000.

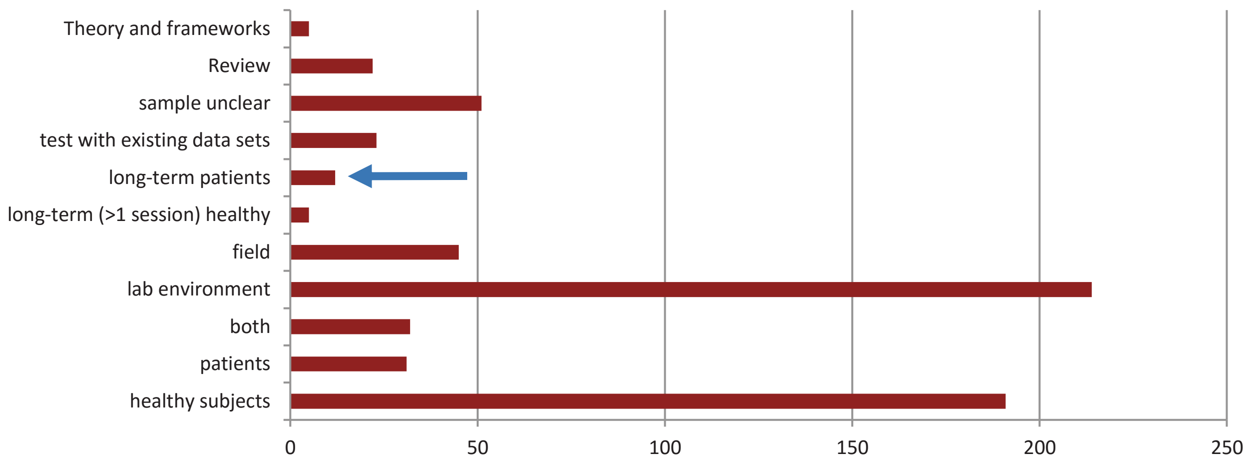


Figure 2: Number of studies (x-axis) per category. It can be clearly seen that the majority of studies was conducted with healthy subjects in the laboratory environment. Studies with patients and in the field are far less in number. The arrow denotes the translational gap.

Most of the studies included healthy subjects and were conducted in the laboratory environment. Patients included were diagnosed with amyotrophic lateral sclerosis (ALS), cerebral palsy, disorders of consciousness (vegetative state, minimally conscious state [MCS], emerging MCS), epilepsy, locked-in syndrome after brain stem stroke, multiple sclerosis, post-stroke aphasia, and spinal cord injury (SCI). Forty-two studies included patients and 32 both healthy participants and patients. If it was not otherwise mentioned, we assumed that the experiment was conducted in the laboratory. Forty-five studies report on data collection in the field. The vast majority of studies report results from one session and only 17 present data from more than one session; of those 12

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were with patients (see Figure 2). The Table provided an overview of some aspects investigated in P300 BCI related papers. Similar effort was invested in how to best separate target from non-target responses. Analysis of classification procedures and the effect of the different manipulations on accuracy, ITR, and usability were considered beyond the scope of this overview.

Table 1: Topics investigated in P300 BCI publications (a full reference list can be ordered from the first author).

| **Presentation of stimuli** | **Stimulation modality, recording, and elicited ERPs** | **P300 BCI set-up** | **Psychological variables potentially influencing P300 BCI performance** | **Predictors of P300-BCI performance** | **P300-BCI controlled applications** |
|---|---|---|---|---|---|
| -Matrix size<br>-Matrix colour<br>Moving matrix<br>-Location of stimuli<br>-Luminance<br>-Size of stimuli<br>-Spatial position of stimuli<br>-Character grouping<br>-Flash rate<br>-Flash pattern<br>-Rapid serial visual presentation<br>-Suppressing stimuli<br>-Faces as stimuli (famous, familiar, inverted)<br>-Facial expression modulation<br>-Avoidance of redundant stimuli<br>-Multi-level matrices<br>-Polyphonic music stimuli<br>-Two-stimulus paradigm | -Stimulus modality: visual, auditory, tactual, multimodal<br>-Additional ERPs (N100, MMN, N150, N200, N400, visual evoked potential (VEP), motion-onset VEP)<br>-Error potentials<br>Input signals (EEG, MEG, ECoG, EOG)<br>-Combination of input signals (hybrid: SMR, SSVEP, EMG, eye movement) | -Inter stimulus interval<br>-Length of P300 segment<br>-Number of channels / sensors<br>-Amount of training data<br>-Source of errors<br>-Asynchronous dynamic stopping of stimuli presentation<br>-Mindfulness training<br>-Dictionary predictive spelling<br>-Language models<br>shared control<br>-Auto-calibration and laymen set-up | -Motivation<br>-Emotion<br>-Satisfaction<br>-Empathy<br>-Cognitive performance<br>-Attention<br>-Memory<br>-Workload<br>-Fatigue | -Heart rate variability<br>-Root-mean-square amplitude<br>-Negative peak amplitude of the target ERP<br>-Auditory oddball P300<br>-Concentration<br>-Working memory<br>-General intelligence | -Spelling<br>-Word presentation<br>-Virtual apartment<br>-Internet surfing<br>-Gaming<br>-Wheelchair control<br>-Brain painting<br>-(Telepresence-) Robot control<br>-Standard assistive technology<br>-Emailing<br>-Prosthesis<br>-Robotic arm<br>-Multimedia player |

## DISCUSSION

A tremendous amount of work to improve the speed and reliability of the P300 BCI has been done in the past 10 years. By now, basic principles of stimulation, presentation, and classification are known [e.g., 4]. Reasons for the impressive increase in research effort may have been better classification algorithms and more sophisticated ways of presenting the stimuli. For example, the introduction of overlaying faces instead of flashes resulted in a boost of performance of up to one repetition sequence with no decrease in accuracy which stayed at 100% [5].

When looking more closely at the success stories, they are mainly attributed to few studies each belonging to specific research groups. Even within the field of the P300 BCI, successful modifications are only reluctantly or not at all taken up by the community. A positive example is the use of SWLDA

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for classification. Contrarily, face stimuli were only taken up by few groups and new ways of stimulus presentation are still compared to the classic P300 spelling matrix instead of the most successful presentation mode at any given point in time.

If the field is seriously aiming at bringing BCIs to end-users in the field, be it patients or healthy subjects, researchers have to leave the laboratory and work in exactly this field. The needs and requirements of end-users must be clearly defined and the few available studies indicated that if researchers make this effort, BCIs are indeed an option for communication and control in daily life [6,7].

## CONCLUSION

The lack of interaction between research groups and integration of results keeps the P300 BCI below its possibilities. We argue that by now, we have sufficient knowledge for standardization and recommendations beyond which current and future research should not fall behind. This knowledge should be thoroughly applied for the benefit of end-users.

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