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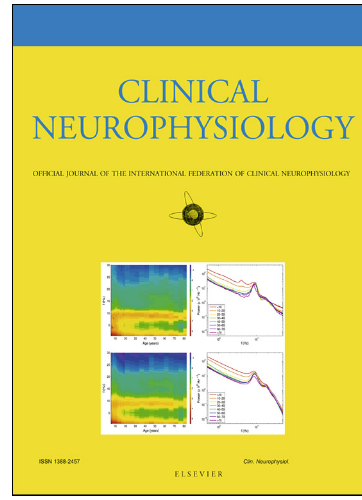

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Effects of training and motivation on auditory P300 brain-computer interface performance

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Highlights

1. Training improves performance with a multi-class auditory P300 speller paradigm.

2. Communication speed after training is one of the highest that has been achieved with auditory brain-computer interface paradigms.

3. Motivation influences BCI performance and P300 amplitude.

Abstract

Objectives: Brain-computer interface (BCI) technology aims at helping end-users with severe motor paralysis to communicate with their environment without using the natural output pathways of the brain. For end-users in complete paralysis, loss of gaze control may necessitate non-visual BCI systems. The present study investigated the effect of training on performance with an auditory P300 multi-class speller paradigm. For half of the participants, spatial cues were added to the auditory stimuli to see whether performance can be further optimized. The influence of motivation, mood and workload on performance and P300 component was also examined.

Methods: In five sessions, 16 healthy participants were instructed to spell several words by attending to animal sounds representing the rows and columns of a 5x5 letter matrix.

Results: 81% of the participants achieved an average online accuracy of ≥70%.

From the first to the fifth session information transfer rates increased from 3.72 bits/min to 5.63 bits/min. Motivation significantly influenced P300 amplitude and online ITR. No significant facilitative effect of spatial cues on performance was observed.

Conclusions: Training improves performance in an auditory BCI paradigm. Motivation influences performance and P300 amplitude.

Significance: The described auditory BCI system may help end-users to communicate independently of gaze control with their environment.

Keywords: EEG; auditory P300; spelling; training effects; motivation; spatial cues.

1. Introduction

Brain-computer interfaces (BCI) recognize patterns in brain activity and translate the brain signals into input commands to artificial devices for control and communication without using the natural output channels of the brain, i.e. peripheral nerves and muscles. Thus, BCIs can enable severely paralyzed people to establish control over assistive devices (Zickler et al., 2011).

The main target population for BCIs consists of patients in the locked-in state (LIS), who are paralyzed with minimal residual movement and have thus, lost the ability to speak, but with full preservation of consciousness (Haig et al., 1987). The complete LIS (CLIS) leaves patients without any voluntary muscular control (Kübler and Birbaumer, 2008) and the big challenge for BCI research remains to be the communication of CLIS patients with their environment.

The present study used the P300 event-related potential (ERP) component, an automatically elicited response of the brain to external stimuli (Sutton et al., 1965). Typically, the P300 response is elicited by the oddball paradigm, in which the target stimuli are presented infrequently among a stream of frequent non-target stimuli. Attention to the rare target stimulus produces a positive peak in electrocortical activity around 300 ms after stimulus onset that can be recorded with electroencephalography (EEG) mainly over centro-parietal areas.

The P300 was first employed as input signal for a BCI by Farwell and Donchin (1988) for choosing items from a 6x6 matrix to spell words. Up to the present time, many BCI research groups used this spelling paradigm, in which the rows and columns comprising letters, numbers (symbols) or commands flash in a random order while the user's brain activity is recorded. The task of the user is to attend to the target in the matrix and mentally count how many times it flashes. Since the target row / column flashes only once out of six times, it is a rare event that elicits a P300 response and this setup constitutes an oddball paradigm. A classification algorithm identifies the row and column with the most prominent P300 and selects the matrix cell accordingly. The P300-based visual BCIs have proven to be highly reliable for communication (for review Fazel-Rezai et al., 2012; Kleih et al., 2011) and they were successfully used by both healthy participants (Donchin and Farwell, 1988; Donchin et al., 2000; Kleih et al., 2010) and paralyzed patients (Kaufmann et al, 2013b; Nijboer et al., 2008b; Sellers and Donchin, 2006; Zickler et al., 2013).

Although the visual P300 speller paradigm was used successfully with locked-in patients in some studies, recent evidence (Brunner et al., 2010; Treder and Blankertz, 2010) suggested that performance in a visual P300 speller was dependent to some extent on gaze control (Kaufmann et al., 2013a; Riccio et al., 2012). These findings indicate that many potential BCI users, who have impairments in ocular muscle control, are likely to have problems in exerting control over their environment through these BCI systems. Hence, there is a clear need for vision-independent BCI systems.

In order to create gaze independent EEG-based BCIs, researchers started to use tactile modality (Brouwer and van Erp, 2010; Cincotti et al., 2007) and auditory modality with binary (Hill et al., 2004; Halder et al.,2010) or multi-class approaches (Furdea et al., 2009; Klobassa et al., 2009; Nijboer et al., 2008a; Sellers and Donchin, 2006).

Of special interest are multi-class BCIs since they can be used for expression of complex contents and thus, can be more advantageous for some tasks and for some groups of users. The same auditory paradigm as used in Furdea and colleagues (Furdea et al., 2009) was tested by Kübler and colleagues (Kübler et al., 2009) with patients who were diagnosed with amyotrophic lateral sclerosis (ALS) and who had been trained with a visual BCI before. The performance did not fulfill the requirements for satisfactory communication (mean accuracy of 13%). The authors emphasized the necessity of further research, suggesting the use of different stimuli like musical tones or to present stimuli with spatial cues.

Later studies showed the utility of spatial information as an additional cue in auditory paradigms. Schreuder and colleagues (Schreuder et al., 2009, 2010, 2011) demonstrated the superiority of performance in spatial condition as compared with non-spatial condition. Similarly, Käthner et al. (2013), and Simon et al. (2015) used virtual directional cues (presented over stereo headphones).

Furthermore, BCI performance does not solely depend on the BCI system. Several studies investigated which user factors influence BCI efficiency and they revealed that factors such as mood and motivation (Nijboer et al., 2008a; 2010) could influence either BCI performance (Kleih et al., 2011) or P300 electrophysiology (Kleih et al, 2010). Such factors may contribute to the observed inter-individual differences.

Summary of study aims

The present study was designed to investigate the effects of user training in an ERP-based auditory multiclass speller paradigm. Auditory paradigms in general impose higher task demands on users (Klobassa et al, 2009; Nijboer et al., 2008a) and selectively attending to target auditory stimuli requires learning. A between subject design was used to ascertain whether participants would benefit from additional spatial information. It was assumed predicted that spatial cues would help participants to discriminate the sounds easier and to allocate their attention to the target sound more efficiently. Accordingly, subjective workload was expected to be lower for the participants who received spatial cues. In order to increase the usability of the system in the home environment of the patients, experimental stimuli were presented via headphones.

Another aim of the present study was to examine the effects of psychological factors on BCI performance and the P300 component. Since it was speculated before that the effect of motivation would be more pronounced with increased task difficulty (Kleih et al., 2010), we hypothesized that motivation would have strong effects in an auditory paradigm. More specifically, we predicted that the P300 amplitudes and BCI performance would be increased with enhanced motivation.

2. Methods

2.1. Participants

The study enrolled sixteen university students (8 female, mean age 23.88, SD ±2.5, age range 19-27) from Universities of Würzburg (N=8) and Tübingen (N=8), who were compensated for participation. Participants reported no history of neurological, psychiatric or chronic diseases, no epilepsy and no auditory impairments. None of them participated in an auditory BCI study before. The experiment was conducted in accordance with standard ethical guidelines as defined by the Declaration of Helsinki (2013 Revision, World Medical Association) and the European Council's Convention for the Protection of Human Rights and Dignity of the Human Being with regard to the Application of Biology and Medicine (Convention on Human Rights and Biomedicine).

2.2. Data Acquisition

The EEG was recorded from 16 Ag/AgCl electrodes located at positions F3, Fz, F4, T7, C3, Cz, C4, T8, Cp3, Cp4, P3, Pz, P4, PO7, PO8, Oz following the modified international 10-20 system standardized by the American Electroencephalographic Society (Sharbrough et al., 1991). The channels were referenced to the right and grounded to the left mastoid. All signals were amplified using a 16-channel g.USBamp amplifier (g.tec Medical Engineering GmbH, Austria). Data were recorded with a sampling rate of 256 Hz, band-pass filtered between 0.1 and 30 Hz, and notch-filtered at 50 Hz. Stimulus presentation and data collection were controlled by the software BCI2000 (Schalk et al., 2004).

2.3. Questionnaires

We administered the short version of the Allgemeine Depressions-Skala (ADS-K; Hautzinger and Bailer, 1993) to ensure that none of the participants had symptoms of depression. None of the participants were above the cut-off value.

Motivation was measured with two different questionnaires, the adapted version (Nijboer et al., 2008a) of the Questionnaire for Current Motivation (QCM; Rheinberg et al., 2001) and a visual analogue scale (VAS). The adapted QCM includes 18 items, rated on a 7-point likert scale, corresponding to four different components of motivation: mastery confidence, incompetence fear, interest and challenge. Participants also indicated their level of motivation on the VAS, a 10cm line ranging from 0 (not motivated at all) to 10 (extremely motivated). Also mood was measured with a VAS on a 10 cm line (0=extremely bad mood, 10=extremely good mood).

The subjective workload of the participants was assessed with the computerized version of NASA-Task Load Index (NASA-TLX; NASA Human Performance Research Group, 1987). The total score ranges between 0-100, with higher scores indicating higher subjective workload. This questionnaire has been shown to provide valuable information about BCI related workload (Holz et al., 2013; Riccio et al., 2011; Zickler et al., 2011; 2013).

Further scales (VAS) were used to measure subjects' satisfaction with the speller and with their own performance (10 cm, 0=not satisfied at all, 10=absolutely satisfied). Additionally, we administered the "d2" test of attention (Brickenkamp and Zillmer, 1998) to ensure that the participants can focus on the task at hand. Also a custom-made questionnaire was administered to assess participants' ability to differentiate between the sounds. These results are not reported in this paper.

2.4. Auditory P300 speller

The stimulus presentation paradigm followed the traditional arrangement of characters in a matrix from the study of Farwell and Donchin (1988). The auditory ERP speller was based on the same principle as the aforementioned visual speller. The traditional 6x6 matrix of items was replaced by a 5x5 matrix to reduce the number of stimuli (as in Furdea et al., 2009). The columns and rows were each coded with a specific animal sound. The sounds representing the rows and columns were presented sequentially; i.e. first only row stimuli, followed by only column stimuli. The participants were instructed to attend to the target sounds representing the coordinates of the letter in the matrix. The letter matrix was displayed on the computer screen to help participants to locate the target letters and to identify which sounds correspond to which rows / columns (Figure 1).

2.5. Auditory stimuli and spatial information

Five animal sounds (duck, bird, frog, seagull, and dove) were used as stimuli, with each sound corresponding to a particular row and column (see Figure 1). This set of sounds was chosen based on performance and subjective ratings of the participants in a pre-study (Ruf et al., 2013; Simon et al., 2015). The sounds were of equal length (150 ms) and loudness, and were presented over circumaural stereo headphones (Sennheiser HD280 Pro). Additionally, half of the participants received directional cues with the sounds. The stimuli were modified to create virtual sound directions over stereo headphones with the procedure described in Käthner and colleagues (Käthner et al., 2013). Sound 1 (duck) was presented on the left channel, sound 5 (dove) only on the right, and sound 3 (frog) on both channels. The basic principles of human sound localization (interaural time difference –ITD- and interaural level difference –ILD-) were used to give the illusion of sounds coming from directions at a particular angle; i.e. sound 2 (bird) and sound 4 (seagull) coming from left and right with approximately 60° of angle respectively.

2.6. Procedure

All participants completed five experimental sessions on five different days, which were two to five days apart. Participants were seated 1 m away from the computer screen, with the screen approximately in the middle of their visual field. The same procedure was applied for every session, with the exception of the d2 test and ADS-K, which were administered once at the beginning of the experiment, and the evaluation (custom made) questionnaire at the end of the last session. In each session, participants completed first the paper and pencil questionnaires of QCM-BCI and VAS for motivation and mood. The experimental stimuli were introduced to the participants until they reported to be able to differentiate between different sounds.

Two sets of words were created for the copy-spelling task (Table 1). The participants completed twelve runs of copy-spelling in each session, and two optional runs of free-spelling. In the copy-spelling runs, the words to spell were always displayed above the visual support matrix, and next to the word appeared the current target character in parenthesis. The task of the participant was to attend to the sound corresponding first to the row containing the target and then to the column, by counting silently the target sound. In the first three calibration runs, 10 sequences of all sounds were presented for each target selection, for each row and column separately.

For both row and column selection, each sequence consisted of the random presentation of the five animal sounds, adding up to a total of 50 sounds. Thus, one trial (needed for selecting one character) consisted of 100 stimulus presentations, with the target probability being 20% (20 target and 80 nontarget sounds). Each sound was presented for 150 ms followed by an inter stimulus interval of 287.5 ms. There were 2s between the presentation of the sounds for rows and columns, and an additional pause of 12 s (6 s pre- and 6 s post trial) was provided between two letter selections to allow subjects to locate the next target and to identify the corresponding sounds.

In the three calibration runs, which were used to train the classifier, no feedback was provided. Participants spelled the matrix diagonal letters “AGSMY”. The data from the calibration runs were used to identify individual parameters by employing the “P300 Classifier” tool provided with the BCI2000 software. The discriminant function generated from these data was used for online classification of the ERPs in the subsequent runs of the same session, for decoding the intended letter and providing feedback to the participant. The data from the calibration was also used to specify the optimum number of sequences. The number of sequences needed to achieve 70% accuracy was estimated for each participant. Two more sequences were added to this number to increase the reliability of communication. Feature weights and number of sequences were individually adapted in every session but remained the same within each session.

At the end of each BCI session, participants rated their satisfaction with the BCI system and with their own performance via VAS. After filling in the custom made questionnaire, subjects completed the NASA-TLX.

2.7. Signal classification

Stepwise linear discriminant analysis (SWLDA, Draper and Smith, 1981) was applied for classification. Previous studies showed that SWLDA provides a robust classification method for visual P300 paradigms (Donchin et al., 2000; Farwell and Donchin, 1988; Sellers and Donchin, 2006), as well as auditory P300 paradigms (Furdea et al., 2009; Halder et al., 2010; Klobassa et al., 2009; Sellers and Donchin, 2006).

SWLDA selects spatiotemporal features, which discriminate best between targets and non-targets. The algorithm adds features to the linear equation until an optimization criterion is reached (until the function includes a predetermined number of features, 60 for the present study).

2.8. Data analysis

EEG data was analyzed with the Brain Vision Analyzer 2.0 (BrainProducts GmbH, Germany). Data was segmented into epochs between 100 ms pre- and 800 ms post-stimulus onset using the first 100 ms for baseline correction. Data from calibration and testing runs were pooled for ERP analysis, since the only difference between them was the feedback that was presented after stimulation. Averages were calculated separately for target and non-targets and condition (spatial vs. non-spatial), per participant and session. The amplitude of the P300 was defined as the maximum positive peak between 300 and 800 ms after the presentation of the target sound. The latency was defined as the interval between onset of target presentation and peak amplitude. In the present study most of the participants had the highest P300 amplitude at Cz, thus, we decided to restrict further analysis to this electrode. Statistical analyses were performed with SPSS 19.0.

The two BCI performance measures effectiveness (accuracy) and efficiency (information transfer rate – ITR) were calculated for each participant to evaluate the system. This terminology follows the user-centered design adapted to BCI controlled applications by Zickler and colleagues (Zickler et al., 2011). Accuracy was defined as the percentage of correct letter selections, whereas the ITR was the amount of information (bits) transmitted per time unit (minute). The most widely used formula was described by Pierce (1980):

$$B = \log2\, N + P \log2\, P + (1 - P) \log2\left(\frac{1-P}{N-1}\right)$$

Where N is for the number of possible targets, P represents the probability of correct classification, and B bits per selection. The ITR (bits/min) was calculated by multiplying B by the average number of selections per minute.

For comparison of the different sounds presented, selection frequencies of each sound were analyzed with repeated measures analysis of variance (ANOVA) to see whether there was a selection bias toward any of the sounds.

2 x 5 repeated measures ANOVAs were calculated with time (session) as within and condition (spatial vs non-spatial) as between subjects' factor to investigate the effects of training on performance and P300 component. Correlation analyses (Pearson's r) were calculated to explore the influence of psychological factors (motivation, mood and workload) on performance, and on P300 amplitude and latency.

3. Results

3.1. Online accuracy and information transfer rates

The mean online accuracy and ITR of each participant in each session are listed in Table 2. All but three participants reached a mean accuracy level (over all sessions) at or above 70%, which was defined as the minimum accuracy level for communication via BCI (Kübler et al., 2001). In the first session 8 of the participants achieved 70% or above accuracy, and this number increased to 12 participant in the final session. The average accuracy was 79% for the spatial group and 76% for the non-spatial group. The number of sequences was adapted individually for each session, resulting in an average of 5.35 for the spatial and 5.33 for the non-spatial group. The highest average ITR reached in a session per participant (including the interval between characters) was 9.33 bits/min for both groups. The spatial group had overall (all sessions) an average ITR of 5.33 bits/min and the non-spatial group 4.93 bits/min (Figure 2).

The 2 (condition) x 5 (session) repeated measures ANOVA with mean accuracy as dependent variable revealed a main effect of session, $F(4, 56) = 5.59$, $p<0.005$, indicating that performance improved with time. The main effect of condition and the condition x session interaction were not significant. The same results were found for ITR (main effect of session:

F(4, 56) = 5.8, *p*<0.005; main effect of condition and interaction ns). Thus, performance in terms of online accuracy and ITR increased with training in both experimental groups. On the data of both groups combined, post hoc tests using Bonferroni correction indicated that performances (ITR) were significantly different (*p* < 0.05) between the first session (*M*=3.72, *SD*=0.57) and the second (*M*=5.23, *SD*=0.46),the first and the third (*M*=5.64, *SD*=0.60) and the first and the fifth sessions (*M*=5.57, *SD*=0.54). The difference between the first and fourth session (*M*=5.49, *SD*=0.54) was marginally significant (*p*=0.081). These results suggest that most of the learning occurred in the beginning of the experimental period, whereas the difference between the remaining sessions was not significant.

3.2. P300 amplitude and latency

The average P300 amplitudes at Cz were 8.35 μV (SD=5.56) for the spatial group, and 12.23 μV (SD=7.63) for the non-spatial group, and the average latencies 558.11 ms (SD=156.22) and 539.75 ms (SD=133.39) respectively.

Two separate 2 (condition) x 5 (session) repeated measures ANOVAs with P300 amplitude and latencies at Cz as dependent variables were calculated and yielded no significant effects. The amplitude and latency of P300 did not change across experimental sessions (for mean values see Table 3).

3.3. Effects of psychological factors

Psychological measures, averaged across five sessions for each group, are summarized in Table 4. The 2 (condition) x 5 (session) ANOVAs revealed that none of the measured psychological variables changed significantly across sessions, with the exception of motivation subscale of interest, *F*(4, 56) = 5.06, *p*<0.05. The interest decreased across sessions in both groups.

All participants' data were pooled together and tested for correlations to see the effects of different psychological factors on performance and P300 features. For these analyses, all threshold levels of significance were adjusted for multiple comparisons by Bonferroni correction.

The motivation subscale interest was significantly correlated with average ITR (r = .74, p<0.001, 1-tailed). A significant positive correlation was found between average motivation (VAS) and average ITR (r=0.7, p<0.005, 1-tailed) and also between VAS motivation and average amplitude of P300 (r =0.57, p<0.05, 1-tailed). To further elucidate the positive correlation between motivation and P300 amplitude, as well as ITR, we divided participants into two groups with respect to their motivation level (median split) and compared the mean ERP amplitudes and ITR of the groups. The P300 amplitude differed between the groups (t(14) = -2.822, p<0.05); participants with high motivation had higher amplitudes (M=14.17, SD=7.29) as compared to those with lower levels of motivation (M=6.41, SD=2.71) (Figure 3). The high motivation group had also higher ITR (M=6.02, SD=1.7) as compared to the low motivation group (M=4.24, SD=1.42), t(14) = -2.27, p<0.05.No other variable was found to influence performance, P300 amplitude and latency.

Independent samples t-tests showed that the two groups in terms of location of data collection were significantly different in terms of VAS motivation (t(14) = -3.7, p<0.005), VAS mood (t(14) = -2.26, p<0.05), P300 amplitude (t(14) = -2.74, p<0.05) and latency (t(14) = 2.31, p<0.05), motivation subscale interest (t(14) = -3.51, p<0.005) and overall workload (t(14) = 2.2, p<0.05). Additional analyses revealed that VAS motivation and mood (r=0.84, p<0.001), motivation and interest (r=0.74, p<0.005), and mood and interest (r=0.57, p<0.05) were correlated.

3.4. Sound comparison

A 2 (condition) x 5 (auditory stimulus) repeated measures ANOVA with selection frequency of each sound as dependent variable was performed to investigate whether there was a selection bias toward any stimuli. The results revealed no significant difference between the selection frequencies of the five sounds $F(4, 56) = 2.45$, $p>0.05$.

4. Discussion

The present study showed that training improves performance in an auditory P300 BCI paradigm. We also demonstrated that motivation of the users had a significant impact on BCI performance and P300 amplitude. Contradictory to our hypothesis, we did not observe a facilitating effect of spatial cues on performance.

4.1. Online accuracy and ITR

In the first session only half of the participants achieved accuracy levels above 70%, however, this number increased to 75% in the final session. Most of the users (81%) achieved an average online accuracy (average of all sessions) of 70% or higher, above the criterion level for satisfactory communication (Kübler et al., 2001b). Participants who were below the criterion level still had lower number of repetitions as compared to the starting value of 10 (see Table 2).

For the present study, ITR constitutes a more appropriate measure than accuracy for comparison of performance between sessions because it contains both variables that change across sessions, namely online accuracy and number of iterations. Participants in both groups improved their ITR with training. The present study resulted in an average online ITR of 5.13 bits/min, which is higher than those reported in studies with similar designs (e.g. Furdea et al., 2009; Klobassa et al., 2009) and among the highest reported in the studies using auditory paradigms and online analysis (for comparison with other BCI studies see Table 5, for a review see Riccio et al., 2012).

4.2. Event related potentials

In the present study, amplitudes and latencies of P300 remained stable throughout the experimental sessions for both groups. This result is in line with the study of Nijboer and colleagues (Nijboer et al., 2008b), which demonstrated that P300 amplitude and latency remained stable over 40 weeks of BCI use in patients with amyotrophic lateral sclerosis.

4.3. Psychological factors

Besides the motivation subscale of interest, all psychological variables remained stable across sessions in both groups. The task of controlling a device by their brain activity may be very interesting for naïve participants; however with experience their initial interest diminishes. Nonetheless, their overall motivation and mood (VAS) did not change throughout the experimental period.

The subjective workload of the participants remained stable in both groups across sessions. Although the workload did not decrease throughout the experimental period, participants increased their performance. In other words, the training did not decrease the subjective workload of the participants, since the change in the number of sequences increased the task difficulty thus balancing the workload. Our hypothesis that the workload would be higher in the non-spatial group was not supported, as the spatial cues did not facilitate performance in the current study.

Psychological states of the participants have been found to influence performance or P300 component in former studies (Kleih et al., 2010, 2011; Nijboer et al., 2008a, 2010). As expected, motivation affected P300 amplitudes; i.e. higher motivation led to higher amplitudes. The finding of a positive relation between motivation and P300 amplitude is not confined to BCI studies. Goldstein and colleagues (Goldstein et al., 2006) showed in a go/no-go task that P300 amplitude increased with higher monetary reward, which was accompanied by increases in interest and excitement ratings. This effect of motivation is likely mediated by the attentional resources participants allocated to the task. Engelmann and colleagues

(Engelmann et al., 2009) stated that there is an interaction between motivation and attention, i.e. stimuli of motivational importance attract more attention and also motivation enhances the effects of attention. Furthermore, it is hypothesized that the amplitude of the P300 is related to the amount of attention allocated to task or stimulus (Kok, 2001; Polich et al., 1995, 2007). Thus, it is plausible that highly motivated participants engaged more attention to the task, which resulted in higher P300 amplitudes. This connection is further supported by the finding that BCI performance (ITR) increased together with motivation (VAS and subscale interest) as in the study of Kleih and colleagues (Kleih et al., 2011). Therefore, we recommend routinely assessing motivation of users.

4.4. Auditory stimuli and spatial information

Although subjects reported having difficulty in distinguishing between some sounds (bird and seagull), in the post-measurement questionnaires they rated the stimuli as adequately discriminable. The selection rates and online performance in both groups indicate that the stimuli were suitable for an auditory P300 speller and they were comparable in their saliency. One of the main challenges in an auditory paradigm is to make the stimuli easily discriminable for the users. Unlike many studies with auditory paradigms using artificial sounds (e.g. Schreuder et al., 2010; 2011), this study used natural sounds as experimental stimuli as in Simon and colleagues (Simon et al., 2015). As shown previously (Höhne et al., 2012; Simon et al., 2015) natural sounds are advantageous for auditory BCIs, since users are already familiar with them and that saves additional training and may reduce workload. One of the main reasons of using non-natural tones (e.g. differing in pitch) is to keep the stimulus duration as short as possible. The presentation time in the present study was of acceptable length, allowing for higher spelling speed as compared with the studies using unnatural sounds.

Contrary to our hypothesis, additional spatial cues did not facilitate performance in the present study. Spatial information added to auditory cues has been found to have a facilitative effect on BCI performance in several former studies (e.g. Höhne et al., 2010; Schreuder et al., 2009; 2010; 2011). In line with the suggestion of Schreuder and colleagues (Schreuder et al., 2011), we argue that if the auditory stimuli are easily discriminable, adding directional cues does not necessarily facilitate performance. However, the spatial information can be used in purely auditory BCIs (without the visual support matrix), where participants can utilize the spatial cues to memorize the matrix and to have an intuitive mapping. Thus, spatial information may reduce the working memory load in purely auditory BCI paradigms.

4.5. Training effects

In the present study we observed that the performance of participants in both groups saturated already at the third session. Thus, this study revealed that a very short period of training (even two – three sessions) can improve performance considerably with healthy users. Most likely, more sessions would be needed for patients.

Besides having several (11) training sessions, Klobassa et al. (2009) also adjusted the number of stimulus presentations according to the performance (offline – only for those who performed well). In their study, low number of repetitions resulted in higher ITRs but insufficient accuracy for BCI communication. The present results suggest that learning can occur much faster and that it is possible to have high ITRs without compromising accuracy.

Participants in both groups performed significantly better in the final session as compared to the first session. Co-adaptation of the user's brain and the computer is an important aspect in BCI research, and users learn in the process of interaction to optimize their behavior to control the BCI device (Zhang et al., 2010). Zhang and colleagues (Zhang et al., 2010) suggested that the higher the demands of a BCI, the more likely the performance will benefit from training. Since auditory paradigms place more demands on cognitive resources as compared to visual paradigms (Nijboer et al., 2008a), it is plausible that people benefit from training in auditory BCIs.

The present results are encouraging and indicate that end users with impairment, who will use BCIs for extended periods, may improve their performance over time. In the present study, the number of iterations was adapted online in each session and this provided participants with the opportunity to increase the ITR and to reach a higher spelling speed. As shown in the current study, performance in a BCI can be influenced by many factors, such as training, stimulus modality and motivation. Although the present study showed that the P300 component remained stable throughout the experimental period, it can be fruitful to calibrate the system for every use in order to optimize the performance of the user and adapt the iteration number.

4.7. Limitations

One limitation of this study is that it is based on healthy participants, which limits our conclusions regarding the end-users (persons with motor impairments). We showed the feasibility of the current paradigm with high ITRs and the next step will be to test it with end-users. Simon and colleagues (Simon et al., 2015) tried the same paradigm with one end-user with ALS and showed that the end-user improved in performance over two sessions, although not achieving sufficient accuracies for communication. Based on this and our findings, we hope that end-users will benefit from training.

Another limitation is the applicability of exact methodology of the current study to an end-user sample. It would be difficult to apply all the questionnaires we used, considering the communication speed of the potential end users and thus the time needed to finish all the questionnaires. Therefore, a study with healthy participants is additionally important to optimize the methodology. Our findings confirmed that motivation is one of the main factors that determine BCI performance. Several studies (e.g. Nijboer et al., 2010; Zickler et al., 2011) showed that it is possible to use questionnaires (like QCM and subjective workload) and scales (visual analogue) with end-users (LIS). With the end-users in CLIS the main challenge is to establish a means of communication. If that is accomplished, we believe very simple scales could be used.

4.8. Conclusion

The current study showed that training improves performance with a multi-class auditory P300 speller paradigm, as tested with healthy participants. Unlike in visual paradigms, participants benefit from training in auditory paradigms, since the task of attending to individual tones that are presented in a rapid sequence while ignoring some others is particularly difficult. Furthermore, it seems useful to include a short calibration phase before every session to increase the speed of communication and to enable optimal performance.

As previously shown (Kleih et al., 2010, 2011; Nijboer et al., 2008a, 2010), the presented results support the assumption that participants' motivation influences BCI performance and P300 amplitude. Therefore, motivational factors should be regularly monitored. Short and simple measures (e.g. VAS) are available for this purpose.

Contrary to the expectations, spatial information did not facilitate performance in the present study. However, this additional cue may make the transition to purely auditory systems easier, since the sound-row/column pairings and the target sound can be inferred from the spatial arrangement of the sounds.

The results of the present study are encouraging for the development and feasibility of auditory paradigms. The usability of the presented paradigm for motor impaired end-users remains to be shown.

Conflict of Interest

None of the authors have potential conflicts of interest to be disclosed.

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References

Birbaumer N. Breaking the silence: brain-computer interfaces (BCI) for communication and motor control. Psychophysiology 2006; 43:517–32.

Birbaumer N, Ghanayim N, Hinterberger T, Iversen I, Kotchoubey B, Kübler A, et al. A spelling device for the paralysed. Nature 1999; 398: 297–98.

Birbaumer N, Kübler A, Ghanayim N, Hinterberger T, Perelmouter J, Kaiser J, et al. The thought translation device (TTD) for completely paralyzed patients. IEEE Trans Rehabil Eng 2000; 8: 190–92.

Brickenkamp R, Zillmer E. The d2 Test of Attention. 1st ed. (D. Emmans, Trans.). Seattle, WA: Hogrefe & Huber Publishers; 1998.

Brouwer AM, van Erp JBF. A tactile P300 brain-computer interface. Front Neurosci 2010; 4:19.

Brunner P, Joshi S, Briskin S, Wolpaw JR, Bischof H, Schalk G. Does the “P300” speller depend on eye gaze? J Neural Eng 2010; 7: 056013.

Cincotti F, Kauhanen L, Aloise F, Palomaki T, Caporusso N, Jylanki P, et al. Vibrotactile feedback for brain–computer interface operation. Comput Intell Neurosci 2007; 2007: 48937.

Donchin E, Cohen L. Averaged evoked potentials and intramodality selective attention. Electroencephalogr Clin Neurophysiol 1967; 22: 537–46.

Donchin E, Spencer KM, Wijesinghe R. The mental prosthesis: Assessing the speed of a P300-based brain-computer interface. IEEE Trans Rehabil Eng 2000; 8: 174 – 79.

Draper N, Smith H. Applied regression analysis. 2nd ed. New York: John Wiley and Sons; 1981.

Engelmann JB, Damaraju E, Padmala S, Pessoa L. Combined effects of attention and motivation on visual task performance: transient and sustained motivational effects. Front Hum Neurosci 2009, 3:4.

Farwell LA, Donchin E. Talking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials. Electroencephalogr Clin Neurophysiol 198; 70: 510–23.

Fazel-Rezai R, Allison BZ, Guger C, Sellers EW, Kleih SC, Kübler A. P300 brain computer interface: current challenges and emerging trends. Front Neuroeng 2012, 5, 1 – 14.

Furdea A, Halder S, Krusienski DJ, Bross D, Nijboer F, Birbaumer, N, et al. An auditory oddball (P300) spelling system for brain-computer interfaces. Psychophysiology 2009; 46: 617–25.

Goldstein RZ, Cottone LA, Jia Z, Maloney T, Volkow ND, Squires NK. The effect of graded monetary reward on cognitive event-related potentials and behavior in young healthy adults. Int J Psychophysiol 2006; 62: 272-79.

Haig AJ, Katz RT, Sahgal V. Mortality and complications of the locked-in syndrome. Arch Phys Med Rehabil 1987; 68: 24 – 7.

Halder S, Rea M, Andreoni R, Nijboer F, Hammer EM, Kleih SC, et al. An auditory oddball brain–computer interface for binary choices. Clin Neurophysiol 2010; 121: 516–23.

Hanagasi HA, Gurvit IH, Ermutlu N, Kaptanoglu G, Karamursel S, Idrisoglu HA, et al. Cognitive impairment in amyotrophic lateral sclerosis: evidence from neuropsychological investigation and event-related potentials. Cogn Brain Res 2002; 14: 234–44.

Hautzinger M, Bailer M. Allgemeine Depressions Skala. Manual. Göttingen: Beltz Test GmbH; 1993.

Hill NJ, Lal TN, Bierig K, Birbaumer N, Schölkopf B. An auditory paradigm for brain-computer interfaces. In: Advances in Neural Information Processing Systems. Cambridge, MA: MIT Press; 2004. p. 569–76.

Hill NJ, Schölkopf B. An online brain-computer interface based on shifting attention to concurrent streams of auditory stimuli. J Neural Eng 2012; 9: 026011.

Holz EM, Höhne J, Staiger-Sälzer P, Tangermann M, Kübler A. Brain-computer interface controlled gaming: evaluation of usability by severely motor restricted end-users. Artif Intell Med 2013; 59: 111-20.

Höhne J, Schreuder M, Blankertz B, Tangermann M. Two-dimensional auditory P300 Speller with predictive text system. Conf Proc IEEE Eng Med Biol Soc 2010; 1: 4185–88.

Höhne J, Schreuder M, Blankertz B, Tangermann M. A novel 9-class auditory ERP paradigm driving a predictive text entry system. Front Neurosci 2011; 5: 99.

Kaufmann T, Holz EM, Kübler A. Comparison of tactile, auditory, and visual modality for brain-computer interface use: a case study with a patient in the locked-in state. Front Neurosci 2013a; 7: 129.

Kaufmann T, Kübler A. Beyond maximum speed—a novel two-stimulus paradigm for brain–computer interfaces based on event-related potentials (P300-BCI). J Neural Eng 2014; **11**: 056004.

Kaufmann T, Schulz SM, Köblitz A, Renner G, Wessig C, Kübler A. Face stimuli effectively prevent brain-computer interface inefficiency in patients with neurodegenerative disease. Clin Neurophysiol 2013b; 124: 893-900.

Käthner I, Ruf CA, Pasqualotto E, Braun C, Birbaumer N, Halder S. A portable auditory P300 brain-computer interface with directional cues. Clin Neurophysiol 2013; 124: 327-38.

Kleih S, Nijboer F, Halder S, Kübler A. Motivation modulates the P300 amplitude during brain-computer interface use. Clin Neurophysiol 2010; 121: 1023–31.

Kleih S, Riccio A, Mattia D, Schreuder M, Tangermann M, Zickler C, et al. Motivation affects performance in a P300 brain computer interface. Int J Bioelectromagn 2011; 13: 46-7.

Klobassa DS, Vaughan TM, Brunner P, Schwartz NE, Wolpaw JR, Neuper C, et al. Toward a high-throughput auditory p300-based brain–computer interface. Clin Neurophysiol 2009; 120: 1252–61.

Kok A. On the utility of P3 amplitude as a measure of processing capacity. Psychophysiology 2001; 38: 557-77.

Krusienski DJ, Sellers EW, Kabestaing F, Bayoudh S, McFarland DJ, Vaughan TM. A comparison of classification techniques for the P300 speller. J Neural Eng 2006; 3: 299–305.

Kübler A, Birbaumer N. Brain–computer interfaces and communication in paralysis: extinction of goal directed thinking in completely paralysed patients? Clin Neurophysiol 2008; 119: 2658–66.

Kübler A, Furdea A, Halder S, Hammer EM, Nijboer F, Kotchoubey B. A brain-computer interface controlled auditory event-related potential (P300) spelling system for locked-in patients. Ann N Y Acad Sci 2009; 1157: 90-100.

Kübler A, Kotchoubey B, Kaiser J, Wolpaw JR, Birbaumer N. Brain–computer communication: unlocking the locked in. Psychol Bull 2001a; 127:358–375.

Kübler A, Neumann N, Kaiser J, Kotchoubey B, Hinterberger T, Birbaumer N. Brain–computer communication: self-regulation of slow cortical potentials for verbal communication. Arch Phys Med Rehabil 2001b; 82: 1533–9.

Lenhardt A, Kaper M, Ritter HJ. An adaptive P300-based online brain computer interface. IEEE Trans Neural Syst Rehabil Eng 2008; 16: 121-30.

Linden D. The P300: where in the brain is it produced and what does it tell us? Neuroscientist 2005; 6: 563–76.

Lule D, Zickler C, Häcker S, Bruno MA, Demertzi A, Pellas F, et al. Life can be worth living in locked-in syndrome. Prog Brain Re 2009; 177: 339 – 51.

NASA Human Performance Research Group. Task Load Index (NASA-TLX) NASA Ames Research Centre, NASA Human Performance Research Group; 1987. http://humansystems.arc.nasa.gov/groups/TLX

Nijboer F, Birbaumer N, Kübler A. The influence of psychological state and motivation on brain-computer interface performance in patients with amyotrophic lateral sclerosis – a longitudinal study. Front Neurosci 2010; 4:55.

Nijboer F, Furdea A, Gunst I, Mellinger J, McFarland DJ, Birbaumer N. An auditory brain-computer interface (BCI). J Neurosci Method 2008a; 167: 43–50.

Nijboer F, Sellers EW, Mellinger J, Jordan MA, Matuz T, Furdea A, et al. A P300-based brain–computer interface for people with amyotrophic lateral sclerosis. Clin Neurophysiol 2008b;119: 1909–16.

Pierce J. An introduction to information theory: symbols, signals & noise. 2nd revised edition. New York: Dover Publications; 1980.

Polich J. Task difficulty, probability, and inter-stimulus interval as determinants of P300 from auditory stimuli. Electroencephalogr Clin Neurophysiol 1987; 68: 311–20.

Polich J. Updating P300: an integrative theory of P3a and P3b. Clin Neurophysiol 2007; 118: 2128 –48.

Polich J, Kok A. Cognitive and biological determinants of P300: an integrative review. Biol Psychol 1995; 41: 103-46.

Rheinberg F, Vollmeyer R, Burns B. FAM: Eine Fragebogen zur Erfassung Aktueller Motivation in Lern- und Leistungssituationen. Diagnostica 2001; 47: 57–66.

Riccio A, Leotta F, Bianchi L, Aloise F, Zickler C, Hoogerwerf EJ, et al. (2011). Workload measurement in a communication application operated through a P300-based brain-computer interface. J Neural Eng 2011; 8: 025028.

Riccio A, Mattia D, Simione L, Olivetti M, Cincotti F. Eye-gaze independent EEG-based brain–computer interfaces for communication. J Neural Eng 2012; 9: 045001.

Ruf CA, Simon N, Käthner I, Pasqualotto E, Birbaumer N, Halder S. (2013). Listen to the frog! An auditory P300 brain-computer interface with directional cues and natural sounds. Proceedings of the Fifth International Brain-Computer Interface Meeting 2013.

Schalk G, McFarland DJ, Hinterberger T, Birbaumer N, Wolpaw JR. (2004). BCI2000: A general-purpose brain–computer interface (BCI) system. IEEE Trans Biomed Eng 2004; 51: 1034–43.

Schreuder M, Blankertz B, Tangermann M. A new auditory multi-class brain–computer interface paradigm: spatial hearing as an informative cue. PloS One 2010; 5: e9813.

Schreuder M, Rost T, Tangermann M. Listen, you are writing! Speeding up online spelling with a dynamic auditory BCI. Front Neurosci 2011; 5: 112.

Schreuder M, Tangermann M, Blankertz B. Initial results of a high-speed spatial auditory BCI. Int J Bioelectrogn 2009; 11: 105–9.

Sellers EW, Donchin E A. P300-based brain–computer interface: initial tests by ALS patients. Clin Neurophysiol 2006;117: 538–48.

Sharbrough F, Chatrian GE, Lesser RP, Lüders H, Nuwer M, Picton TW.American electroencephalographic society guidelines for standard electrode position nomenclature. J Clin Neurophysiol 1991; 8: 200–2.

Simon N, Käthner I, Ruf CA, Pasqualotto E, Kübler A, Halder S. An auditory multiclass brain-computer interface with natural stimuli: Usability evaluation with healthy participants and a motor impaired end user. Front Hum Neurosci 2015; 8: 1039.

Spierer L, Tardif E, Sperdin H, Murray MM, Clarke S. Learning-induced plasticity in auditory spatial representations revealed by electrical neuroimaging. J Neurosci 2007; 27: 5474 –83.

Sutton S, Braren M, Zublin J, John E. Evoked potential correlates of stimulus uncertainty. Science 1965; 150: 1187–8.

Treder MS, Blankertz B. (C)overt attention and visual speller design in an ERP based brain–computer interface. Behav Brain Funct 2010; 6: 28.

Wolpaw JR, Birbaumer N, McFarland D, Pfurtscheller G, Vaughan T. Brain-computer interfaces for communication and control. Clin Neurophysiol 2002; 113: 767–91.

World Medical Association. World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. JAMA 2013; 310: 2191-4

Zhang D, Maye A, Gao X, Hong B, Engel AK, Gao S. An independent brain-computer interface using covert non-spatial visual selective attention. J Neural Eng 2010; 7: 016010.

Zickler C, Halder S, Kleih SC, Herbert C, Kübler A. Brain Painting: usability testing according to the user-centered design in end users with severe motor paralysis. Artif Intell Med 2013; 59: 99-110.

Zickler C, Riccio A, Leotta F, Hillian-Tress S, Halder S, Holz E, et al.A brain-computer interface as input channel for a standard assistive technology software. Clin EEG Neurosci 2011; 42: 236-44.

Zillmer EA, Kennedy CH. Construct validity for the d2 test of attention. Arch Clin Neuropsychol 1999; 14: 728.

Figure Legends

Figure 1. An example of the visual support matrix with the copy-spelling word (HUNGER) and the feedback (CUN) provided to the participant. For instance, to choose the letter "H" the participant was required to attend to the bird sound during the first half of the trial and on frog sound during the second half. In this example, participant made a mistake in the first letter and wrote C instead of H. Participants were requested to ignore the error and to continue with copy spelling.

Figure 2. Averaged bit rates per session for each group. Error bars represent the standard error of the mean.

Figure 3. ERP P300 of the participants at electrode Cz with respect to the level of their motivation (high vs. low motivation).

Figure 1

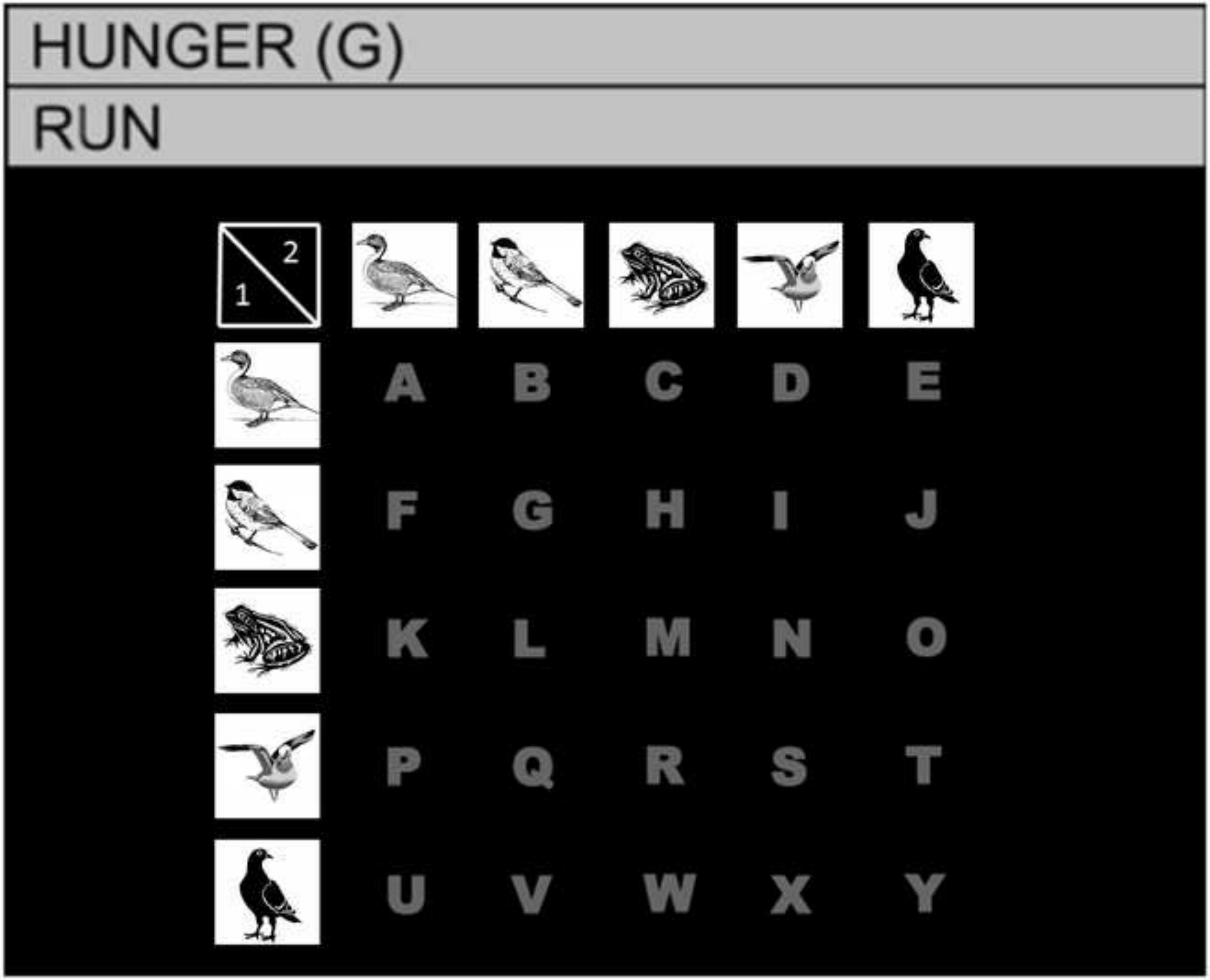

Figure 2

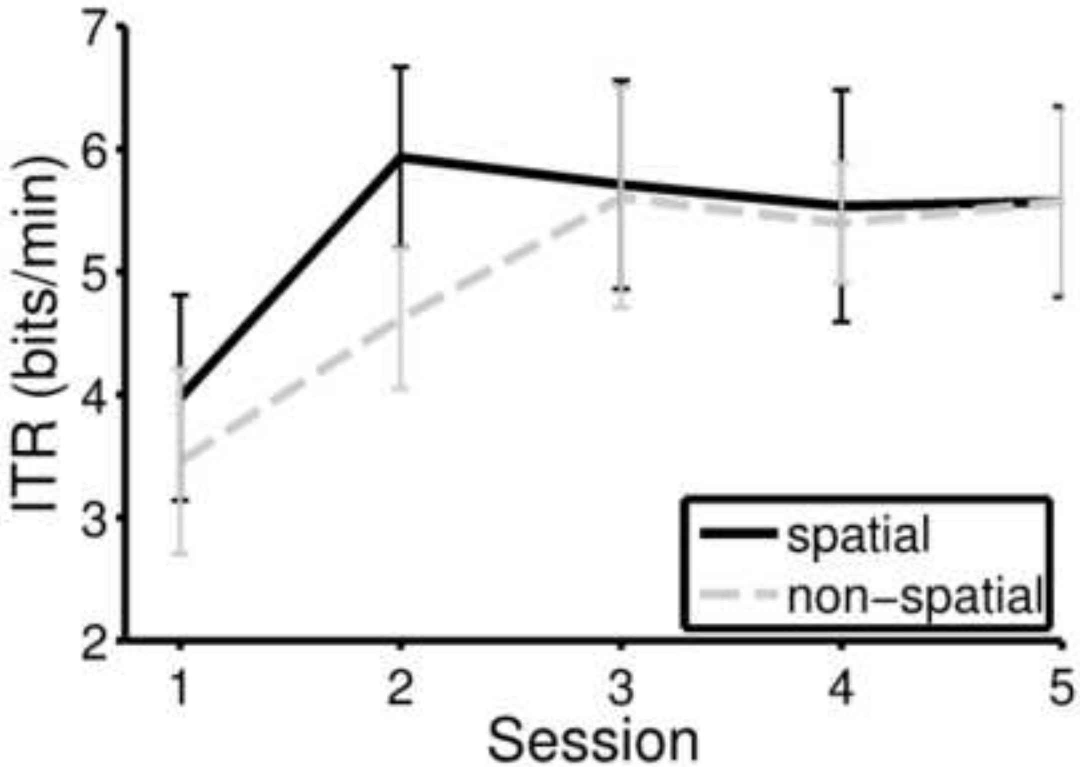

Figure 3

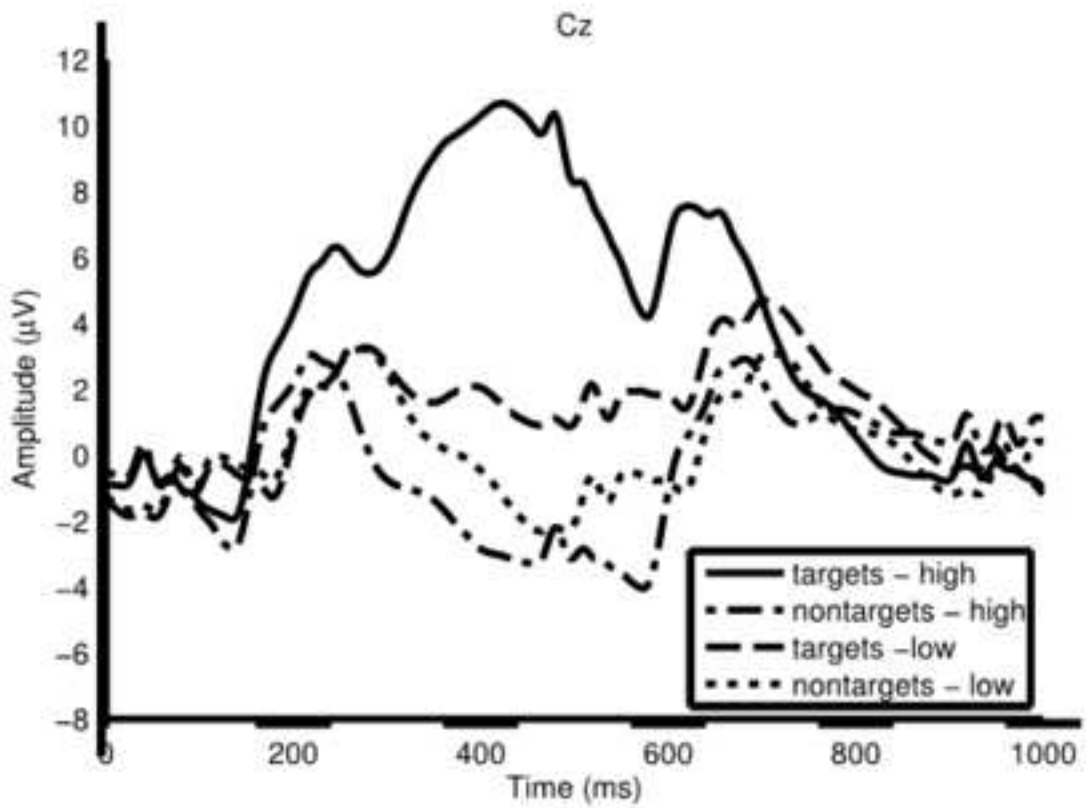
Cz
12
10
8
6
4
2
0
−2
−4
−6
−8
Amplitude (μV)
0
200
400
600
800
1000
Time (ms)
targets – high
nontargets – high
targets –low
nontargets – low

Table 1. Spelled words in individual sessions. First list was used in the first two sessions; the second list in the following two. In the fifth session, a mixture of two lists was used.

	Session 1&2 online	**Session 3&4 online**	**Session 5 online**
Screening	AGMSY AGMSY AGMSY	AGMSY AGMSY AGMSY	AGMSY AGMSY AGMSY
Letters to be spelled	15	15	15
Copy Spelling	VARIO GRUEN HUNGER TUMBI RUBIO VALERI UMBIT PHLEX VIRAGO	KIRVE GORAX QUENCH AYRIL LURIE GROUND DOGRU RAYLI TAKVIM	PHLEX LURIE GROUND DOGRU TUMBI HUNGER RUBIO GRUEN QUENCH
Letters to be spelled	48	48	48
Free Spelling	2 x 5-6 letter word of own choice	2 x 5-6 letter word of own choice	2 x 5-6 letter word of own choice
Letters to be spelled	10-12	10-12	10-12

Table 2. Online accuracies and information transfer rates in spatial and non-spatial groups averaged across five sessions (SD in parentheses).

	Spatial Group

Participant	Average Accuracy (%)	Average ITR (bits/min)	Average number of sequences
1	87 (7)	5.3 (1.1)	6 (1.9)
2	55 (7)	1.9 (0.4)	8,8 (1.8)
3	75 (14)	4.5 (1.5)	5.4 (1.1)
4	80 (7)	5.2 (0.7)	4.8 (0.4)
5	98 (1)	8.9 (0.6)	3.6 (0.5)
6	89 (7)	7.1 (1.9)	4.2 (1.6)
7	74 (15)	4.7 (2)	4.8 (0.4)
8	77 (17)	5.2 (2.4)	5.2 (1.8)
Mean Spatial	79.33 (15.31)	5.33 (2.35)	5.35 (1.93)

	Non-spatial Group		
Participant	Average Accuracy (%)	Average ITR (bits/min)	Average number of sequences
9	51 (15)	2.1 (1.2)	7 (1.9)
10	81 (19)	5.0 (2.1)	6 (1.4)
11	80 (1)	4.9 (0.9)	5.4 (1.3)
12	80 (10)	5.6 (1.5)	4.4 (0.9)
13	90 (4)	7.4 (1.1)	3.8 (0.4)
14	85 (8)	6.1 (2)	4.6 (1.1)
15	78 (10)	4.9 (1.6)	5.4 (2.6)
16	66 (14)	3.6 (1.5)	6 (2.3)

Mean Non-spatial	76.46 (15.67)	4.95 (2.06)	5.33 (1.79)

Table 3. P300 amplitude and latencies across sessions, average of both groups.

	P300 Amplitude (μV)		P300 Latency (ms)	
Sessions	Mean	SD	Mean	SD
1	8.90	6.61	576.12	123.1
2	10.35	6.71	551.22	147.8
3	10.51	6.48	541.7	157.02
4	10.49	7.64	541.94	152.39
5	11.19	7.73	533.64	155.38

Table 4. Psychological measures averaged across five sessions for all participants in spatial and non-spatial groups.

	Spatial Group (N=8)		Nonspatial Group (N=8)	
Psychological measures	Mean	SD	Mean	SD
Motivation (VAS)	7.63	1.37	8.10	0.95
Mood (VAS)	7.21	0.90	8.07	1.04
Confidence (QCM)	5.28	0.55	5.29	0.52
Fear (QCM)	2.33	0.98	2.31	1.28
Interest (QCM)	4.45	1.10	4.19	1.26
Challenge (QCM)	4.59	0.83	5.01	0.55
Overall workload (NASA)	56.20	11.40	59.46	8.89
BCI Satisfaction (VAS)	7.19	1.60	6.76	1.80
Self Satisfaction (VAS)	6.33	1.08	6.60	1.63

Table 5. Comparison of BCI paradigms in terms of number of classes, accuracy, ITR, analysis and population studied.

Study	Modality	Number of classes	Accuracy(%)	ITR(bits/min)	Analysis	Population
Hill et al. (2004)	Auditory	2	72.6	1.41	Offline	Healthy
Sellers and Donchin (2006)	Auditory	4	65.4	0.43 – 1.80	Offline	Healthy
Furdea et al. (2009)	Auditory	25	65	1.54	Online	Healthy
Klobassa et al. (2009)	Auditory	36	59.4	1.86	Online	Healthy
Kübler et al. (2009)	Auditory	25	12.1	0.05	Online	ALS patients
Halder et al. (2010)	Auditory	2	78.5	2.46	Offline	Healthy
Höhne et al. (2011)	Auditory	9	89.4	4.61	Online	Healthy
Schreuder et al. (2011)	Auditory	6	86.1	5.13	Online	Healthy
Hill and Schölkopf (2012)	Auditory	2	84.8	4.38	Online	Healthy
Nijboer et al. (2008b)	Visual	36	78.8	9.7	Online	ALS patients
Lenhardt et al. (2008)	Visual	36	65.5 – 87.5	29.35 – 50.61	Online	Healthy
Furdea et al. (2009)	Visual	36	94.6	6.8	Online	Healthy
Kaufmann and Kübler (2014)	Visual	36	81.2	106.2	Offline	Healthy