Gaze-independent brain–computer interfaces based on covert attention and feature attention

To cite this article: M S Treder *et al* 2011 *J. Neural Eng.* **8** 066003

OPEN ACCESS
IOP PUBLISHING JOURNAL OF NEURAL ENGINEERING
J. Neural Eng. **8** (2011) 066003 (12pp) doi:10.1088/1741-2560/8/6/066003

Gaze-independent brain–computer interfaces based on covert attention and feature attention

M S Treder, N M Schmidt and B Blankertz

Machine Learning Laboratory, Berlin Institute of Technology, Berlin, Germany

E-mail: matthias.treder@tu-berlin.de, nico.schmidt@uzh.ch and benjamin.blankertz@tu-berlin.de

Received 1 April 2011
Accepted for publication 15 August 2011
Published 6 October 2011
Online at stacks.iop.org/JNE/8/066003

Abstract
There is evidence that conventional visual brain–computer interfaces (BCIs) based on event-related potentials cannot be operated efficiently when eye movements are not allowed. To overcome this limitation, the aim of this study was to develop a visual speller that does not require eye movements. Three different variants of a two-stage visual speller based on covert spatial attention and non-spatial feature attention (i.e. attention to colour and form) were tested in an online experiment with 13 healthy participants. All participants achieved highly accurate BCI control. They could select one out of thirty symbols (chance level 3.3%) with mean accuracies of 88%–97% for the different spellers. The best results were obtained for a speller that was operated using non-spatial feature attention only. These results show that, using feature attention, it is possible to realize high-accuracy, fast-paced visual spellers that have a large vocabulary and are independent of eye gaze.

S Online supplementary data available from stacks.iop.org/JNE/8/066003/mmedia

(Some figures in this article are in colour only in the electronic version)

Background

The designated goal of a brain–computer interface (BCI) is to establish a direct link from the brain to a machine, thereby circumventing motor behaviour. A popular approach in BCI research is the use of the event-related potential (ERP); that is, the brain response to an internal or external event such as a sensory stimulus. The neural processing of a sensory stimulus is associated with positive and negative ERP components that can be extracted from the electroencephalogram (EEG). Many ERP-based BCIs use the oddball paradigm, wherein attention to a rare sensory event enhances the amplitude of ERP components.

For more than 20 years, the Matrix Speller (aka P300 Speller) has been the backbone of research on ERP-based BCIs [1]. Essentially, the Matrix Speller is a mental typewriter consisting of symbols laid out in rows and columns. The user attends to a particular symbol while rows and columns are intensified (highlighted) in a pseudo-random order. The attended symbol can be inferred from the modulations of the ERP. In the initial Farwell and Donchin study, healthy participants were able to communicate about 2.3 symbols/min. This was followed by numerous studies in which virtually all aspects of the paradigm have been subject to investigation and improvement, for instance classification techniques [2–4], optimization of the intensification sequence and analysis of refractory effects [5], variations in stimulus onset asynchrony (SOA) [6, 7] and new intensification types such as size enhancement and motion [5, 8, 9]. Furthermore, there have been reports of successful implementation in patients' home environments [10, 11]. The continuing interest in the Matrix Speller, as reflected in the sheer number of related publications, bears testimony to its significant impact on the research field.

This merit notwithstanding, recent evidence raised the question of whether a different speller design might be more useful for patients with severe oculomotor impairments. Several studies showed that the Matrix Speller is highly accurate only in overt attention mode; that is, when participants are allowed to fixate the target symbol with their eyes [12, 13, 18]. In a covert attention mode, wherein participants had to fixate the centre of the screen and covertly attend to the target letter in the visual periphery, classification performance deteriorated substantially. It is true that P300 amplitude might have been attenuated because of the difficulty of the task (i.e. participants had to fixate one location but attend to another location). Nevertheless, it was mainly the absence of early occipital components that led to the deterioration of classification performance. There is compelling evidence that these components are modulated by overt attention and exploited by classifiers [12–15][1]. There is no doubt that these components can be affected by mechanisms of top-down attention. For instance, as reviewed in [16], the amplitude of P1 and N1 components following a visual stimulus is known to be enhanced when the stimulus is presented at the attended spatial location compared to a non-attended location. Moreover, [17] suggested that the N2pc component, a negativation arising 175–300 ms post-stimulus, is associated with the attentional selection of targets. Nevertheless, in a recent BCI study Frenzel *et al* [18] demonstrated that early occipital components are also substantially affected by bottom-up processing at the locus of eye gaze. In their study, participants had to attend to a specific symbol in a 3 × 3 Matrix Speller. At the same time, they had to maintain fixation on either the same symbol as the attended symbol (overt attention) or on a different symbol (covert attention). An occipital N200 was observed when the fixated symbol was intensified, even in the covert attention condition where it was not the attended symbol. In contrast, a P300 was evident when the attended symbol was intensified, irrespective of whether or not it was fixated. In line with this, a classifier trained to detect fixated symbols did not detect attended symbols and vice versa. Concluding, Frenzel *et al*'s study suggests that the occipital N200 component mainly indexes the locus of eye gaze and that the P300 mainly indexes the locus of attention.

The fact that efficient use of the Matrix Speller requires eye movement to some extent limits its scope to patients with intact or mildly impaired oculomotor control. Moreover, eye gaze can be assessed more directly by measuring the electrooculogram (EOG) or determining the direction of gaze using an eyetracker. Eyetrackers and EOG-based systems have been shown to be serious alternatives to the Matrix Speller. First, for eyetrackers a communication rate of about 10 words/min was obtained with healthy participants [19]. This is superior to the communication rate typically obtained with EEG-based Matrix Spellers, and even superior to the rate reported using invasive electrocorticography (average 17 symbols/min for one subject) [20]. Second, in a comparative study in which the Matrix Speller was contrasted with a system using four EOG electrodes, the communication rate using EOG was roughly five times higher than for EEG-based communication [21].

Given the high accuracy and pace at which eye gaze can be inferred based on non-neural physiological signals, we believe that the primary field of visual BCI application is situations where these signals are unreliable, such as in patients with impaired eye movement (for a similar argument, see [22]). One way to achieve this is to resort to other sensory modalities, since they are independent of eye gaze. Lately, significant advances have been made in non-visual modalities using auditory [23–25] or tactile [26] stimulation. Nevertheless, visual spellers remain an appealing branch of BCI research, worthwhile to be further pursued. There is evidence that the P300 component has a larger amplitude when elicited by a visual stimulus than when elicited by an auditory stimulus [27, 28]. In line with this, a comparative BCI study on different modalities using the oddball paradigm yielded high selection accuracy for visual stimuli (93%) but not for auditory (70%) and tactile stimuli (68%) [29]. Furthermore, communication using the visual modality is intuitive, because symbols are selected by allocating visual attention to them. With auditory or tactile approaches, mapping is more arbitrary, that is, the correspondence between a particular symbol and an auditory or tactile stimulus needs to be learned and remembered. However, one does not need to abandon the visual modality in order to establish a gaze-independent ERP speller. For instance, Sellers and Donchin showed earlier that non-spatial attention to one out of four sequentially presented words can be used to operate a visual speller [10, 30].

The aim of this study was to use innovative speller design in order to realize high-accuracy, fast-paced visual BCIs that are independent of eye gaze. The starting point was our previous offline study, where we showed that a different speller design can alleviate some of the difficulties faced by the Matrix Speller [12]. In that study, we compared the performance of the Matrix Speller to the performance of an alternative speller called Hex-o-Spell. Based on the original Hex-o-Spell operated by motor imagery [31, 32], the ERP Hex-o-Spell consists of six discs arranged in a circular fashion. The symbol selection process is broken down into two successive stages. At the first stage, each of the six discs contains a different quintet of symbols (e.g., the upper disc contains 'ABCDE'). Upon choice of a symbol group, the symbols of this group are expanded on the other discs and the target symbol can be chosen. In our previous study, offline classification in the covert attention condition revealed unsatisfactory accuracies for both spellers (40% for the Matrix Speller and 60% for the Hex-o-Spell). Nevertheless, the performance of the Hex-o-Spell was 50% better than the performance of the Matrix Speller. We attributed this to the fact that the Hex-o-Spell features few large elements instead of many small elements as in the Matrix Speller, easing the deployment of covert attention and counteracting crowding and the decline of visual acuity in peripheral vision.

For this study, we revised speller design. In particular, the previous ERP Hex-o-Spell and virtually all other visual

[1] In light of this, a general term such as ERP speller seems more adequate than the commonly used term P300 Speller, because it captures the fact that a multitude of ERP components can be modulated in the visual oddball paradigm.

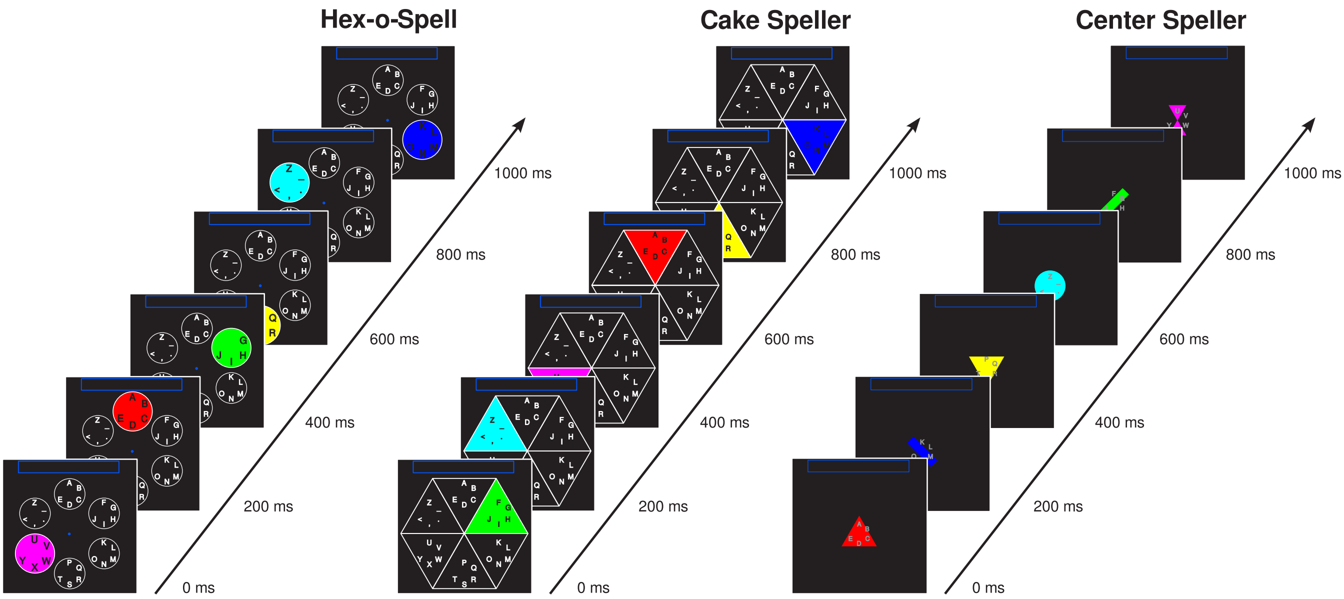

Figure 1. Intensification sequence for each of the spellers. In the Hex-o-Spell, discs were intensified by sizing them up and flashing them with a unique colour. In the Cake Speller, triangular faces were intensified by flashing them in a unique colour. In the Center Speller, elements were presented one after the other. Each element had both a unique colour and a unique shape. The time between subsequent onsets of intensifications was 200 ms. Each element was intensified for 100 ms. In the 100 ms gap after offset of the intensification and before onset of the next intensification, all elements were in their non-intensified state in the Hex-o-Spell and Cake Speller and the screen was blank in the Center Speller (not depicted in the figure).

spellers are not optimal in the sense that they are based on spatial attention alone. It is true that covert spatial attention is associated with a modulation of even early occipital components such as N1 and P1 (for more details, see [16]). However, there are other forms of attention that can also be exploited by BCIs. For instance, humans can selectively attend to particular visual features such as colour and motion, a process called feature attention [33]. Roughly speaking, visual features are the building blocks of perceived objects and they are combined in a perceptual process called feature integration. A comprehensive theory on feature integration was presented by Treisman and Gelade [34]. Feature attention is non-spatial because it does not need to be deployed to a particular spatial location. To give an example, if one attends to the colour red and this colour is sufficiently different from the colour of other (distracter) items, a red object will 'pop out' irrespective of the location of the object in the visual field and irrespective of the number of distracters [35].

To exploit both covert spatial attention and feature attention (in our case, attention to colour and attention to form), we created three enhanced variations of the ERP Hex-o-Spell presented in [12]. The spellers are schematically depicted in figure 1. For each of the three spellers, participants traversed a calibration phase, a free spelling phase where a pre-defined sentence had to be spelled, and another free spelling phase where a self-chosen sentence had to be spelled. A separate classifier was trained for each speller. We based classification on linear discriminant analysis (LDA) with shrinkage of the covariance matrix. Shrinkage LDA (SLDA) was shown to be at least as good as stepwise LDA while being computationally more efficient [36]. The preliminary results of this study were published earlier [37].

Methods

Participants

Thirteen participants (eight males and five females), aged 16–45 years (mean age 27), took part in the experiment. The second author was one of the participants, and another one participated in the precursor study [12]. The other participants were naïve with respect to BCIs. All but one were right-handed and they received money for their participation. All participants had normal or corrected-to-normal visual acuity. Normal colour vision in all but one participant was confirmed using the Ishihara colour vision test [38]. All participants gave written consent and the study was performed in accordance with the Declaration of Helsinki.

Apparatus

EEG was recorded at 1000 Hz, using a Brain Products (Munich, Germany) actiCAP active electrode system with 64 electrodes. We used electrodes Fp2, AF3,4, Fz, F1–10, FCz, FC1–6, T7,8, Cz, C1–6, TP7,8, CPz, CP1–6, Pz, P1–10, POz, PO3,4,7–10, Oz,1,2 and Iz,1,2, placed according to the international 10–10 system. Active electrodes were referenced to left mastoids, using a forehead ground. For offline analysis, electrodes were re-referenced to linked mastoids. All skin–electrode impedances were kept below 20 kΩ. The bandpass of the hardware filter was 0.016–250 Hz. Concurrently with EEG recording, an Intelligaze IG-30 (Alea Technologies, Teltow, Germany) eyetracker, sampling at 50 Hz, was used to register eye movements. Stimuli were presented on a 19″ TFT screen with a refresh rate of 60 Hz and a resolution of 1280 × 1024 px^2. The eyetracker was mounted underneath the screen.

A photodiode was attached to the lower left corner of the screen in order to register the exact onset of the stimuli using a g.trigBox (Guger Technologies, Graz, Austria).

Stimuli

Visual stimulation was achieved using three variations of the ERP Hex-o-Spell introduced in [12], see figure 1. It allows us to choose one out of 30 different symbols comprising the letters of the English alphabet, punctuation marks '.' and ',', a space symbol and a backspace symbol that could be used to erase the previous symbol. Hex-o-Spell is a two-stage speller, where a symbol group (e.g., 'ABCDE') is selected at the first stage. Upon selection of a group, the symbols of that group are expanded on the other discs so that, at the second stage, the target symbol can be selected. Also, at the second stage, the sixth symbol (top left) is empty. This symbol serves as a backdoor and it can be used to return to the group stage in case a wrong group was selected by the classifier.

The original Hex-o-Spell design was enhanced such that participants could use both covert spatial attention and feature attention for selecting symbols. The first variant is a straightforward extension of the Hex-o-Spell. It consists of six discs arranged in a circular fashion. Intensification is provided in form of a size enhancement. At the same time, the corresponding disc is flashed in a unique colour. In other words, participants can both covertly attend to the target disc's spatial location and/or attend to the colour associated with the target disc. When not intensified, all discs have a black background colour. The second variant, called Cake Speller, has a similar layout but instead of six discs it consists of six triangles joining to a hexagon. Analogous to the Hex-o-Spell, each triangle is tagged by a unique colour. Participants can again use covert spatial attention and colour attention to focus on the target. We conjectured that this speller could outperform the Hex-o-Spell because each triangle extends to the central point of fixation, which should ease the deployment of covert spatial attention. In the third variant, called Center Speller, the discs were replaced by unique geometric shapes, each one having a unique colour. In contrast to the Hex-o-Spell and the Cake Speller, shapes are presented centrally in a sequential fashion. We conceive of the selection process in the Center Speller as non-spatial (cf [10, 30] for earlier non-spatial paradigms). It is true that participants attend to the spatial location at which stimuli are presented. However, spatial attention alone enhances the response to all stimuli presented at the attended location, that is, both targets and nontargets. It is therefore the visual features (colours and shapes) that entail attentional selection.

In the Hex-o-Spell, the centres of the six discs were located at a distance of about 7.34° of visual angle from the central fixation point. Each disc had a diameter of 5.67° when not intensified and 6.80° when intensified. In the Cake Speller, the side length of each triangle was 10.65°. In the Center Speller, the sizes of the elements differed for the different shapes, triangle (side length 5.67°), bar (5.1°× 1.41°), circle (diameter 5.1°) and hourglass (2.83°× 5.67°). All spellers featured the same set of six colours. Their luminances, given in candela/m^2, amounted to 39.4 (red), 76.7 (green), 14.6 (blue), 165.2 (yellow), 45.1 (magenta), and 143.7 (grey). The luminance of the black background was 0.1. Michelson contrast [39], defined as $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, was > 98% for all six colours. The duration of a single intensification was 100 ms and visual presentation was time-locked with the screen refresh. SOA, that is, the time between the onsets of subsequent intensifications, was 200 ms.

Procedure

Participants were seated in a comfortable chair at a distance of about 60 cm from the screen. This viewing distance was implicitly controlled by the limited operating range of the eyetracker (60 ± 10 cm). Instruction was given in both written and verbal forms. Participants were instructed to sit still, relax their muscles and try to minimize eye movements during the course of a trial. After EEG preparation and calibration of the eyetracker, they first completed a short standard oddball task. Subsequently, for each of the three spellers, participants traversed a calibration phase and two free spelling phases. The order of the spellers was counterbalanced across participants. In the calibration phase, they had to copy-spell the three words 'WINKT QUARZ FJORD'. There was no feedback and EEG was recorded for offline analysis.

After calibration and training of the classifier, the online phase commenced. Participants had to spell the sentence 'LET YOUR BRAIN TALK', including spaces. They were instructed to use the backdoor symbol if the classifier chose a wrong group, and to use the backspace symbol if a wrong symbol was chosen. If correction of a wrongly spelled symbol did not succeed after two attempts, participants were instructed to skip the current letter and proceed to the next one. In the second free spelling phase, participants were asked to conceive of a sentence containing about 20 symbols. Other than that, instructions were the same as in the previous free spelling phase.

Each trial (corresponding to a single symbol selection) started with a 5 s countdown. During the countdown, participants were allowed to move their gaze freely and memorize the target location and/or feature. The previously spelled letters were shown in a box above the speller. After the countdown, the intensification phase started, lasting for about 30 s in total. In order to ease the deployment of attention, participants were instructed to silently count the number of intensifications of the target symbol. For each of the two stages of the speller, ten sequences of intensifications were presented, whereby each sequence consisted of an intensification of each of the six elements, yielding a total of $10 \times 6 = 60$ intensifications per stage. The order of intensifications was randomized but there had to be at least two intermittent intensifications before a particular symbol was repeated.

For all three spellers, participants had to strictly fixate the centre of the screen while counting target intensifications. To assure proper fixation, eye movements were monitored online. If a fixation of a location other than the centre was detected during the stimulation sequence, a warning tone was presented and the trial was aborted and restarted with another 5 s countdown. All spellers were implemented in the open-source framework Pyff [40] using VisionEgg [41] and remote-controlled via MATLAB (The MathWorks, Natick, MA, USA). The spellers used in the present experiment and in previous studies are freely available in the Pyff repository (see `http://bbci.de/pyff`). Videos exemplifying each of the three spellers being operated in online mode are included as supplemental material available at stacks.iop.org/JNE/8/066003/mmedia.

Data analysis

For offline ERP analysis, the data were downsampled to 250 Hz and lowpass filtered below 49 Hz using a Chebyshev filter (with passbands and stopbands of 42 and 49 Hz, respectively). The data were sectioned into overlapping epochs ranging from −200 ms prestimulus to 800 ms poststimulus. The prestimulus interval was used for baseline correction.

For both online and offline classification, the data were downsampled to 100 Hz and no software filter was applied. Classification was based on LDA with shrinkage of the covariance matrix [36]. As spatial features, we considered all electrodes except for Fp2 and AF3,4, because the latter were unlikely to contribute substantially to classification of the ERP components of interest (i.e., occipital components and P300). For temporal feature selection, we used a heuristic searching for peaks in the point-biserial correlation coefficient $sgn\ r^2$ between targets and nontargets in the 100–700 ms poststimulus interval (see [36] for a more detailed description). Typically, between four and seven temporal windows were selected, and voltages were averaged within these windows. Occasionally, the intervals chosen by the algorithm were adjusted by the experimenter. After each choice of the intervals, cross-validation was used to estimate classification performance. Training of the classifier and cross-validation was based on the calibration data obtained for each speller.

Results

Behavioral compliance

Participants had to fixate a central fixation dot in the case of the Hex-o-Spell and the Cake Speller, or the centrally presented symbols in the case of the Center Speller. As explicated in the methods section, a trial was aborted and restarted if the eyetracker detected a fixation away from the designated fixation point. Overall, behavioral compliance of the participants was high. The means and standard deviations of the percentage of aborted trials are 6.16% ± 4.81% (Hex-o-Spell), 6.34% ± 4.67% (Cake Speller), and 2.05% ± 1.39% (Center Speller). An analysis of variance (ANOVA) revealed a significant difference in the percentage aborted trials across the different spellers ($F = 4.88$, $p < .05$). Tukey–Kramer *post hoc* tests showed that compliance was significantly higher (i.e. fewer aborted trials) for the Center Speller than for the other two spellers.These effects are probably due to the fact that the location of the fixation point and the location of the targets coincides for the Center Speller but not for the other two spellers. The difference between Hex-o-Spell and Cake Speller was not significant. Note that all aborted trials were discarded from ERP analysis and classification.

Event-related potentials

Grand average event-related potentials (ERPs) for each of the three spellers are depicted in figure 2. To test whether ERP amplitude and ERP latency differed across spellers, we subjected the data to a two-way ANOVA, with factors *Speller* (Center Speller, Cake Speller, Hex-o-Spell) and *Electrode* (Fz, Cz, Pz). We restricted statistical tests to the P3 component, because the earlier ERP components were pronounced in the Center Speller but not in the Hex-o-Spell and the Cake Speller. P3 amplitudes and P3 latencies were extracted from the 300–500 ms poststimulus interval.

The analysis of P3 amplitudes revealed a significant effect of *Speller* ($F = 16.61$, $p < .001$) but not $Electrode$ ($p = .3$). $Speller \times Electrode$ interaction was not significant ($p = .16$). Tukey–Kramer *post hoc* tests showed that P3 amplitudes were higher for the Center Speller than for the other two spellers. However, there was no significant difference between Hex-o-Spell and Cake Speller.

Statistical analysis of P3 latencies revealed significant effects of *Speller* ($F = 5.82$, $p < .01$) but not $Electrode$ ($p = .12$). $Speller \times Electrode$ interaction was not significant ($p = .67$). Mean latencies, averaged across the three electrodes, were 356 ms (Hex-o-Spell), 375 ms (Center Speller) and 334 ms (Cake Speller). Tukey–Kramer *post hoc* tests revealed that latencies were higher for the Center Speller than for the Cake Speller. Other pairwise differences were not statistically significant.

Classification

Online classification results are depicted in figure 3(a). Online selection accuracy for selecting one symbol out of 30 (chance level 3.3%) was 91.3% ± 2.6% for the Hex-o-Spell, 88.2% ± 2.6% for the Cake Speller and 97.1% ± 1.5% for the Center Speller. To test whether there was a statistically significant difference between the performances of the spellers, we conducted a one-way ANOVA yielding a statistically significant effect of Speller ($F = 3.87$, $p < .05$). Tukey–Kramer *post hoc* tests revealed that the difference between the Cake Speller and the Center Speller is significant, but not the difference between the Center Speller and the Hex-o-Spell. However, the latter might have been caused by a ceiling effect in the Center Speller.

In an offline analysis, we investigated classification performance as a function of the number of sequences (i.e. repetitions of the intensification). The results are depicted in figure 3(b). As expected, performance increases sharply with the number of repetitions. A two-way ANOVA revealed an increase of accuracy with the number of sequences ($F = 84.85$, $p < .001$), and difference in overall accuracy for the three spellers ($F = 42.92$, $p < .001$). Interaction was not significant ($p = .7$). Tukey–Kramer *post hoc* tests showed that the Center Speller yields a significantly higher accuracy than both the Hex-o-Spell and the Cake Speller.

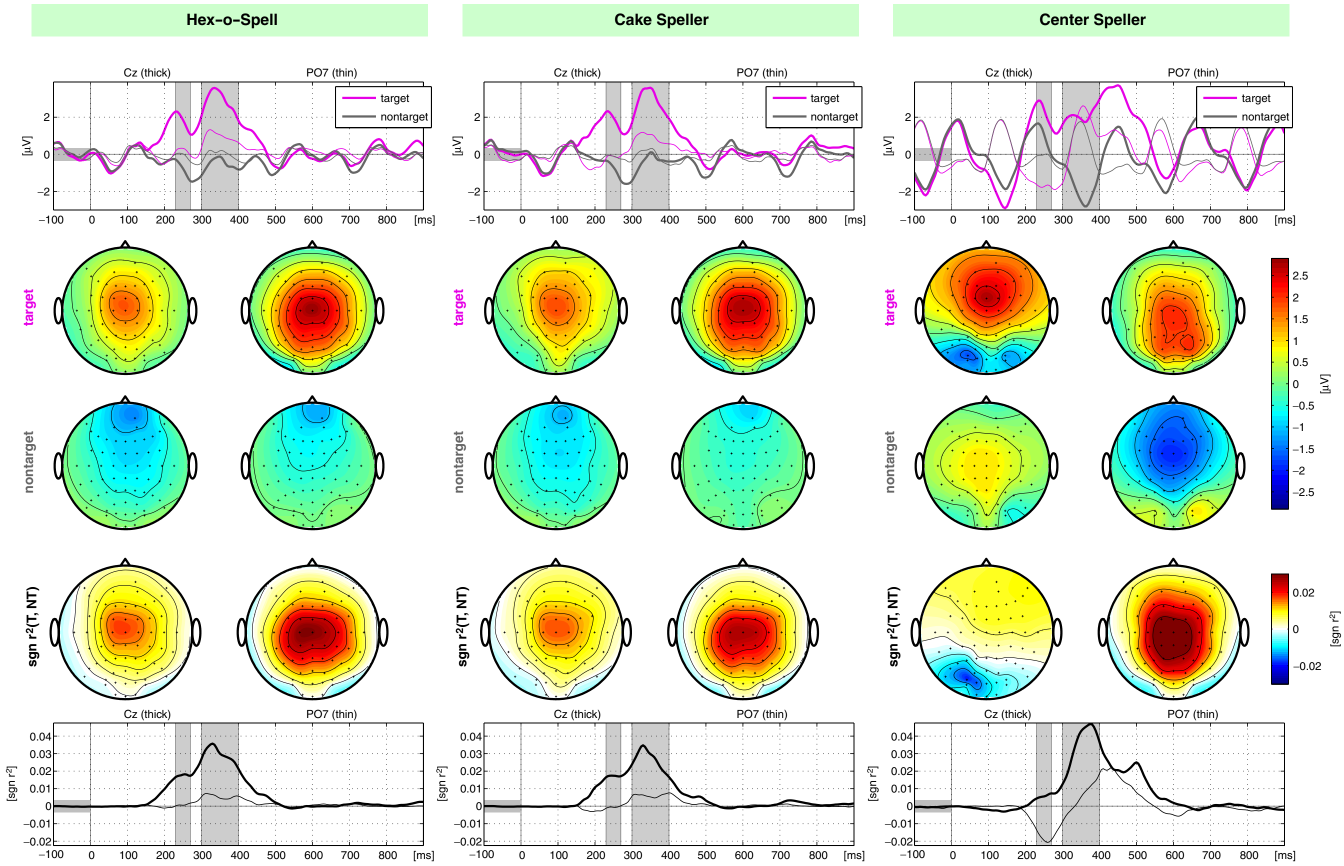

Figure 2. Grand average ERPs for Hex-o-Spell, Cake Speller and Center Speller. Top row: ERPs for targets and nontargets for two selected electrodes Cz and PO7. The two shaded areas in each plot mark the intervals for which scalp maps are shown underneath. Middle: the first row of scalp plots shows the ERP response to targets in the two marked intervals, and the second row shows the response to nontargets. The third row gives $sgn\ r^2$, the signed correlation coefficient, which indicates the difference between target and nontarget classes. Bottom row: $sgn\ r^2$ is plotted as a function of time for electrodes Cz and PO7. The latter plot shows that the P3 component shows a higher discriminability for the Center Speller than for the two other spellers (thick line). Additionally, the Center Speller features an earlier occipital component that is class discriminative (thin line). This component is also evident in the respective scalp plots.

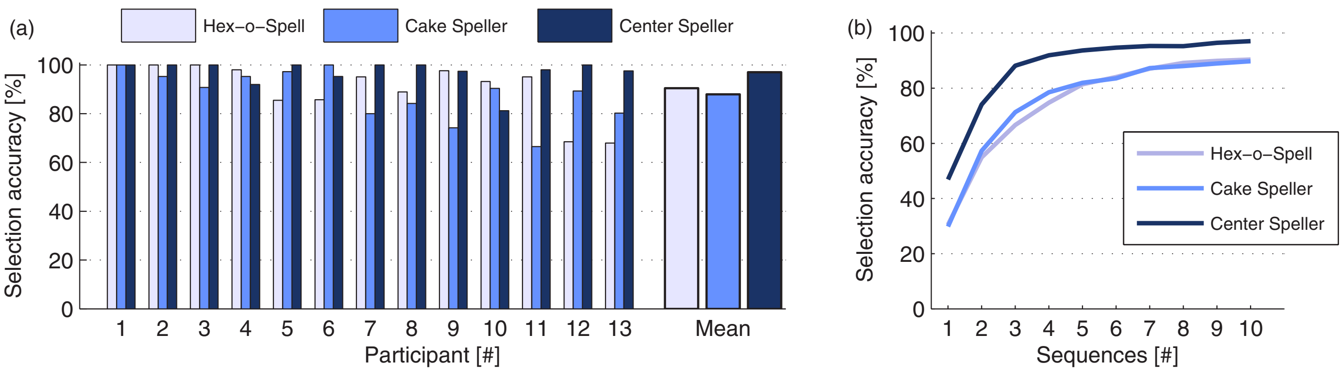

Figure 3. Symbol selection accuracy for online and offline analyses. (a) Online symbol selection accuracy for each participant and for each type of speller. Participants are ordered according to their average performance. The mean accuracy over all participants is given on the right-hand side. The graph shows that each participant achieved online BCI control with each type of speller. For most participants, performance of the Center Speller is equal to or better than the performance of the other two spellers. (b) Results for the offline simulation using a different numbers of sequences. Each line represents the mean accuracy across all participants for a particular speller. The performance of the Center Speller is better than the performance of the other two spellers.

Stimulus specific effects

The stimuli differ with respect to colour and location in the Hex-o-Spell and the Cake Speller, and with respect to colour and shape in the Center Speller. With the current experimental design, we are not able to fully dissociate the effects of different feature types and locations on classification. Therefore, a detailed analysis requires further investigations where the impact of the different features is systematically isolated. As a preliminary analysis, we calculated confusion matrices (i.e.

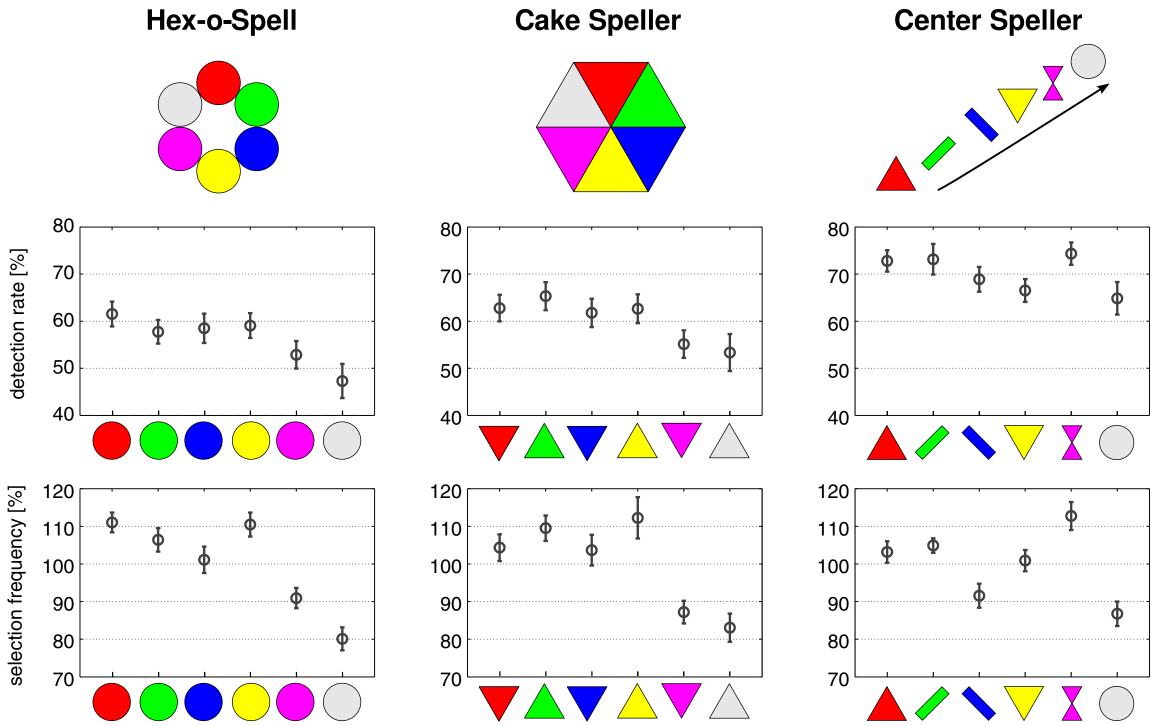

Figure 4. Detectability of the different types of stimuli. Upper panels show the rate of correct detections and lower panels show the frequency of how often each type of stimuli was selected by the classifier during offline classification for each round of six stimuli. In the plots, circles mark the mean and bars the standard error of the respective distributions.

Table 1. Specification of the reduced electrode sets.

Electrode set	Electrode labels	Number of electrodes
Sellers and Donchin	Fz Cz Pz Oz Fp1,2 F3,4 C3,4 P3,4 P7,8 T7,8	16
Liu *et al*	Fz Cz Pz Oz P3,4	6
Central	Fz Cz,3,4 P3,4	6
Occipital	O1,2 PO3,4,7,8	6
Best-4 and Best-6	variable	4 and 6

the six-by-six matrix of true class versus estimated class) for each round of six stimuli. The normalized confusion matrices have been averaged across all participants. Figure 4 shows the diagonal of the confusion matrix, i.e. the rate of correct detections of each class of stimuli (upper panels) and the mean across the true classes, i.e. the percentage of selections of each class (lower panels).

A one-way ANOVA performed on the detection rates revealed a significant effect of the target for Hex-o-Spell ($F = 2.45$, $p < .05$), but not for the Cake Speller ($p = .08$) and the Center Speller ($p = .22$). Figure 4 suggests that in Hex-o-Spell and the Cake Speller, the magenta and grey coloured stimuli have been detected less accurately than the others. In the Center Speller, the magenta coloured hourglass was selected most often (false positives), while the grey coloured circle and the blue bar have been selected least often by the classifier.

Reduced electrode montage

To investigate the impact on performance of reducing the number of electrodes, we performed offline classification using different reduced montages. As before, temporal feature selection was based on peaks in the point-biserial correlation coefficient. Five intervals were automatically selected. Except for this, the classification was analogous to online classification. We compared the full montage to six different reduced montages, four *a priori* (i.e. predefined) montages and two *a posteriori* (*Best*) montages that were determined in a data-driven manner. Two of the *a priori* montages were taken from the ERP-speller studies by Sellers and Donchin [10] and Liu *et al* [42]. In addition, we defined a *Central* montage, with electrodes located at frontal, central and parietal electrode sites, and an *Occipital* montage, with electrodes located at parieto-occipital and occipital electrode sites. The electrode sets are specified in table 1. The *a posteriori* montages *Best-4* and *Best-6* with four and six electrodes, respectively, were determined separately for each participant. We used an iterative procedure that, in the BCI field, was used as part of SWLDA for feature dimensionality reduction [1, 3, 43] and was used here for reduction of the electrode set. Electrode selection was based on the calibration data. For details on the algorithm, see [44].

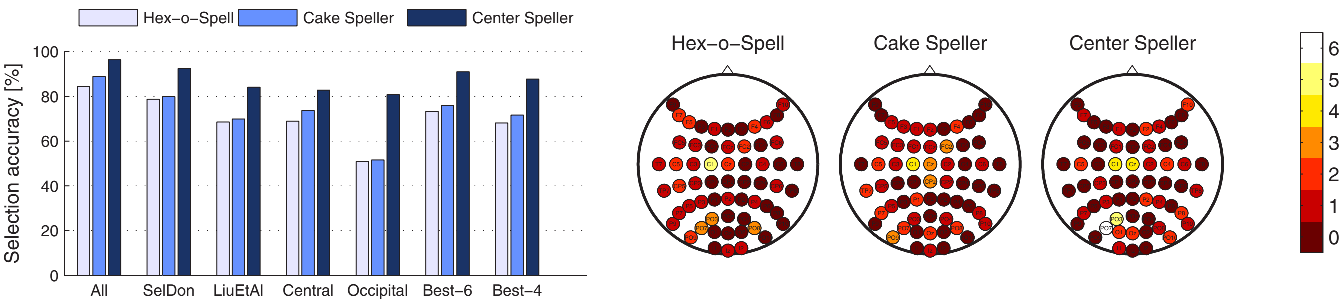

Figure 5. Results of the offline simulation using reduced montages. Left: stacked bars represent results for the three spellers. For all spellers, best performance is achieved with the full electrode set. With the occipital setup, performance deteriorates for the Hex-o-Spell and the Cake Speller but not for the Center Speller. The *Best-6* montage yields a better performance than the other six-electrode montages Liu *et al*, *Central* and *Occipital*, but this difference was not statistically significant. Right: selection frequencies for scalp electrodes using the *Best-6* montage, summed over participants. The distribution of selected electrodes is broad, with more electrodes selected on the left scalp than on the right scalp. For the Hex-o-Spell and the Cake Speller, the most often selected electrode is C1. For the Center Speller, PO7 is selected most often.

The results, depicted in figure 5, show that classification performance is high even when the number of electrodes is substantially lower than in the full electrode set. When only occipital electrodes are used, performance deteriorates substantially in the Hex-o-Spell and in the Cake Speller but it remains fairly stable in the Center Speller. This suggests that the occipital components in the Center Speller are more class discriminative than the components in the other two spellers. To substantiate these observations, we performed a two-way ANOVA. Main effects results were significant for both *Montage* ($F = 9.49$, $p < .001$) and *Speller* ($F = 24.19$, $p < .001$), but interaction was not significant ($p = .86$). Tukey–Kramer *post hoc* tests revealed that the Center Speller yields a better performance than the other two spellers. The *Occipital* montage gave significantly worse classification results than the other montages. The *All* montage performed significantly better than all other montages except for *SelDon* and *Best-6*. The differences between the other montages were not significant.

Discussion

Recent studies raised the question of whether a novel speller design might be more useful for patients with oculomotor impairments [12]. These studies left unanswered, however, whether visual spellers can be realized that operate independently of eye gaze. Proof of concept for this was first given in [37, 45] and was expanded on in this paper. We devised three variants of a gaze-independent speller operating by means of covert spatial attention and/or non-spatial feature attention. For each of the three spellers Hex-o-Spell, Cake Speller and Center Speller, we obtained high selection accuracies during online spelling (91.3%, 88.2% and 97.1%, respectively). All participants were able to successfully operate each of the three spellers.

The neurophysiological analysis showed that the most prominent ERP component is the P300. In the Center Speller, we also consistently found a class-discriminative occipital N200. Similar early components were found for the Hex-o-Spell and the Cake Speller in many participants, but they were highly variable across participants and hence did not surface in the grand average. Furthermore, the highest ERP amplitudes were achieved with the Center Speller where both target and nontarget elements were sequentially presented at a single spatial location. We conjecture that this might be a direct consequence of cortical magnification, which refers to the fact that a disproportionally large amount of neural tissue in visual cortex is devoted to the fovea, so that more neurons are recruited for visual processing [46]. If cortical magnification played a role, one would expect all ERP components, including those following nontarget intensifications, to be enhanced in the Center Speller. Indeed, the ERP plots in figure 2 show that nontarget amplitudes (grey curves) are roughly two times higher for the Center Speller than for the other two spellers. These results are compatible with Frenzel *et al* [18] who, using a Matrix Speller, reported clear N200 components only if the fixated symbol was intensified, irrespective of whether or not it was also the attended symbol.

Classification rates were higher for the Center Speller than for the other two spellers. Apart from the corticial magnification hypothesis, one might argue that the attention task was easier in the Center Speller because participants deployed attention to the same spatial location that they fixated with their eyes. This seems to be supported by the P300 amplitude being higher in the Center Speller than in the other two spellers. However, it is somewhat contradicted by the fact that P300 latencies were highest in the Center Speller, whereas an easier detection task would be associated with shorter latencies. Hence, neurophysiological evidence regarding the hardness of the attention task is not conclusive.

Furthermore, the classification rates revealed little or no difference between the Hex-o-Spell and the Cake Speller, despite our expectation that the Cake Speller should perform better because its faces extend to the point of fixation. We conjecture that this beneficial aspect of the Cake Speller might have been counteracted by the fact that the six faces adjoined each other in the Cake Speller but not the Hex-o-Spell. In other words, it might have been easier to deploy attention to the discs in the Hex-o-Spell and ignore the other discs because there was a clear spatial separation between them. An improved visual speller design could consider a compromise between both spellers. In particular, one could use triangular faces that extend close to the fixation point but that are spatially separated.

Optimization

The purpose of this study was to establish robust classification using gaze-independent visual BCIs. But in order to be useful for patients, a BCI warrants a sufficiently high information throughput. At the current speed and using ten repetitions, information throughput averages to about two characters or 9.8 bits per minute. However, as the offline analysis suggests, the number of repetitions can be cut down from ten to five repetitions with little performance loss, especially for the Center Speller. A more sophisticated approach is to implement a statistical evaluation of classifier outputs entailing stopping the stimulus sequence when there is enough evidence favouring a particular target [47]. The algorithm adapts the number of sequences online and, therefore, it can potentially account for changes in mental states (e.g., lapses of attention and fatigue).

Speed optimization should go hand in hand with a further robustification of the BCI. In particular, we pursue optimization of the visual presentation. To this end, we performed an analysis of stimulus specific effects on classification. Although the present design does not allow us to fully dissociate the effects of the different visual features (location, colour and form), it seems that some spatial directions are more difficult to attend to than others and/or some colours and forms are more perceptually salient than others. In the Hex-o-Spell and the Cake Speller, the red, green and yellow elements were selected most often, suggesting that both contrast and semantic effects (e.g., red is a signal colour) might be relevant. In all three spellers, the grey element was selected least often, suggesting that the monochromatic elements are less salient than chromatic elements. In the Center Speller, it was striking that the hourglass-shaped element was the shape selected most frequently. We assume that this is due to the presence of edges at the point of fixation, which dovetails nicely with the fact that parts of the primary visual system serve as edge detectors [48]. Building on this analysis, we are currently conducting parametric experiments where the visual feature dimensions are dissociated. This allows us to estimate the contribution to classification success of each feature dimension and thereby also allows the identification of ideal combinations of features. Based on this, one could homogenize the perceptual salience of the different elements in order to balance the selection rates.

A different approach builds on the user's perception of BCI feedback. The presentation of erroneous classification output elicits a characteristic ERP, the so-called error potential [49–51]. To date, there have been few comprehensive studies investigating error potentials in online scenarios. Spüler [50] showed that the online detection of error potentials in a Matrix Speller increases communication speed, both for healthy participants and patients with motor disorders. Schmidt *et al* [52] performed online error detection using the Center Speller and reported a significant increase in communication speed. Overall, results suggest that the benefit of error potential detection correlates negatively with the accuracy of symbol classification. In other words, participants with low performance profit more than participants with high performance.

For clinical applicability, it is desirable to use only a small subset of electrodes for classification. Our offline classification results using different reduced montages support the idea that the number of electrodes can be cut from 64 to six electrodes without substantial loss of performance. However, in line with the literature [53], we showed that *a posteriori* montages selected individually for each participant based on statistical criteria are more effective than pre-defined montages. It needs to be evaluated whether this selection is stable across sessions. If so, in clinical trials one might first perform a measurement using high-density EEG and subsequently determine a reduced electrode set tailored to the individual patient.

Gaze (in)dependence

The extent to which a BCI relies on eye movements is germane to the application of a BCI to patients with impaired eye movements. In a closed-loop system, eye gaze dependencies may arise at two distinct steps. First, the BCI may rely on visual stimulation. This is the case for the Matrix Speller, the BCIs presented here, and other BCIs based on visual ERPs or SSVEPs. Second, even if a BCI uses endogenous components (such as voluntary modulations of the sensorimotor rhythm), BCI feedback is often presented in the visual modality. To account for oculomotor impairments, the feedback should not require eye movements, or it should be presented in a different sensory modality.

The present study accompanies a gradual paradigm shift in various strands of BCI research. There is growing awareness that the issue of gaze (in)dependence is relevant and that gaze-independent BCIs form a significant complement to more conventional BCIs. So far, advances can be pinpointed for three types of visual BCI.

First, Acqualagna *et al* [54] used a rapid serial visual presentation (RSVP) paradigm, where 30 different symbols were presented at fixation in sequential bursts of ten symbols. A mean offline selection accuracy of up to 90% was obtained for selecting one symbol out of 30 (chance level 3.33%). Liu *et al* [42] and Aricó *et al* [55] successfully adapted the visual design of the Matrix Speller so as to make it less dependent on eye gaze. In both studies, a visual layout similar to the Hex-o-Spell was used, that is, six letters arranged in a circular fashion around a central fixation point. The main difference was that, upon an intensification, a set of letters was replaced by another set, with each set corresponding to a row or column of the Matrix Speller. High classification accuracies of over 80% [55] and over 90% [42] have been reported.

Second, systems based on the steady state visually evoked potential (SSVEP) exploit the fact that stimulation by a flickering stimulus elicits an increase of spectral EEG power at the stimulation frequency [56]. Usually foveation of the flickering target is required [22], but more recent research addressed the possibility of modulating the SSVEP independently of eye gaze using two different kinds of attention. In Kelly *et al*'s study [57], participants used covert spatial attention to select one out of two flickering targets, located to the left and right of the fixation point. Mean classification accuracy was 71%. In a different approach, Allison *et al* [58] used two overlapping flickering gratings. Participants attended to one of the gratings by means of non-spatial selective attention. Although classification was not performed, the authors reported a significant modulation of SSVEP amplitude by attention. Müller *et al* demonstrated that when attention is deployed to one of two overlapping dot clouds flickering at different frequencies, the SSVEP response to the attended stimulus is enhanced [59]. Subsequently, in a similar paradigm, Zhang *et al* [60] used two overlapping dot clouds rotating in opposite directions and flickering at different frequencies. The attended dot cloud could be classified with an accuracy of about 73%.

Third, a growing number of studies using EEG and MEG investigate the modulation of oscillatory alpha activity as a BCI input modality [57, 61–65]. Shifts of visual attention induce changes in oscillatory alpha activity. For covert attention shifts in different directions, the changes in alpha power have characteristic topographic distributions at occipital electrode sites. Kelly *et al* [66] were the first to show that alpha changes following attention shifts to the right or left form a viable input signal for visual BCIs. Using MEG, these results were expanded upon, showing that multiple directions of attention shifts can be differentiated [62, 63] and that arbitrary directions can be predicted [61]. Later, it was shown that these results transfer to EEG and that the best-classifiable pair of directions differs substantially across participants [64, 65]. The particular appeal of this approach is that it requires no external visual stimulation. In other words, instead of measuring the effects of selective attention on the neural response to visual stimulation, the process of orienting visual attention is directly tapped.

Limitations

Three caveats to present-day approaches to visual BCIs warrant consideration. First, approaches based on SSVEP and alpha activity currently yield feasible performance only when binary classification problems are considered. In contrast, the ERP spellers presented here address the selection of one out of 30 symbols (chance level 3.3%) with high accuracy. Consequently, information throughput is substantially higher for ERP spellers than for the other two approaches.

Second, in gaze-independent visual spellers, elements are usually either presented in a sequential fashion (such as in the Center Speller and in the RSVP speller [54]) or located in the visual periphery (such as in the Hex-o-Spell and in the Cake Speller). In both cases, it might be hard to identify which feature and/or spatial location the participant should attend. For patients with severe oculomotor impairments, the possible choices should be indicated prior to the beginning of stimulation, which would create an experimental overhead. However, this overhead would apply only to the initial phase of BCI usage, since our experience is that spatial locations and visual features are quickly memorized and associated with target symbols.

Third, extreme cases of oculomotor impairment may pose problems even for gaze-independent BCIs. For instance, some patients suffer from involuntary gaze drifts. In such a case, the stimulus would slip into the visual periphery which could impair BCI performance. This problem applies mainly to ERP-based and SSVEP-based BCIs, because they rely on external stimulation. There are no countermeasures so far, but a possible scenario could be to keep track of the patient's eye gaze using an eyetracker and, in the case of a gaze drift, relocate the stimulus so that it is constantly foveated.

Conclusions

Using covert spatial attention and non-spatial feature attention, high-accuracy, fast-paced visual spellers can be realized that have a large vocabulary and that are independent of eye gaze. This broadens the scope of ERP spellers to recovering attentional focus independent of eye gaze. Potentially, this can benefit a larger patient population, including those patients that suffer from severely impaired eye movements.

Acknowledgments

We are indebted to the reviewers, whose constructive comments on the original version of this paper helped to improve it. We would also like to thank Martijn Schreuder for directing us to the automated electrode selection using stepwise LDA.

References

[1] Farwell L and Donchin E 1988 Talking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials *Electroencephalogr. Clin. Neurophysiol.* **70** 510–23

[2] Donchin E, Spencer K M and Wijesinghe R 2000 The mental prosthesis: assessing the speed of a P300-based brain–computer interface *IEEE Trans. Rehabil. Eng.* **8** 174–9

[3] Krusienski D J, Sellers E W, Cabestaing F, Bayoudh S, McFarland D J, Vaughan T M and Wolpaw J R 2006 A comparison of classification techniques for the P300 speller *J. Neural Eng.* **3** 299–305

[4] Rakotomamonjy A and Guigue V 2008 BCI competition III: dataset II- ensemble of SVMs for BCI P300 speller *IEEE Trans. Biomed. Eng.* **55** 1147–54

[5] Martens S M, Hill N J, Farquhar J and Schölkopf B 2009 Overlap and refractory effects in a brain–computer interface speller based on the visual P300 event-related potential *J. Neural Eng.* **6** 026003

[6] Allison B Z and Pineda J A 2006 Effects of SOA and flash pattern manipulations on ERPs, performance and preference: implications for a BCI system *Int. J. Psychophysiol.* **59** 127–40

[7] Sellers E, Krusienski D, McFarland D, Vaughan T and Wolpaw J 2006 A P300 event-related potential brain–computer interface (BCI): the effects of matrix size and inter stimulus interval on performance *Biol. Psychol.* **73** 242–52

[8] Gibert G, Attina V, Mattout J, Maby E and Bertrand O 2008 Size enhancement coupled with intensification of symbols

improves speller accuracy *Proc. of the 4th Int. BCI Workshop and Training Course* pp 250–5

[9] Liu T, Goldberg L, Gao S and Hong B 2010 An online brain–computer interface using non-flashing visual evoked potentials *J. Neural Eng.* **7** 036003

[10] Sellers E W and Donchin E 2006 A P300-based brain–computer interface: initial tests by ALS patients *Clin. Neurophysiol.* **117** 538–48

[11] Sellers E W, Vaughan T M and Wolpaw J R 2010 A brain–computer interface for long-term independent home use *Amyotrophic Lateral Sclerosis* **11** 449–55

[12] Treder M S and Blankertz B 2010 (C)overt attention and visual speller design in an ERP-based brain–computer interface *Behav. Brain Funct.* **6** 28

[13] Brunner P, Joshi S, Briskin S, Wolpaw J R, Bischof H and Schalk G 2010 Does the 'P300' speller depend on eye gaze? *J. Neural. Eng.* **7** 056013

[14] Shishkin S L, Ganin I P, Basyul I A, Zhigalov A Y and Kaplan A Y 2009 N1 wave in the P300 BCI is not sensitive to the physical characteristics of stimuli *J. Integr. Neurosci.* **8** 471–85

[15] Bianchi L, Sami S, Hillebrand A, Fawcett I P, Quitadamo L R and Seri S 2010 Which physiological components are more suitable for visual ERP based brain–computer interface? A preliminary MEG/EEG study *Brain Topogr.* **23** 180–5

[16] Hillyard S A and Anllo-Vento L 1998 Event-related brain potentials in the study of visual selective attention *Proc. Natl Acad. Sci. USA* **95** 781–7

[17] Hickey C, McDonald J J and Theeuwes J 2006 Electrophysiological evidence of the capture of visual attention *J. Cogn. Neurosci.* **18** 604–13

[18] Frenzel S, Neubert E and Bandt C 2011 Two communication lines in a 3 × 3 matrix speller *J. Neural Eng.* **8** 036021

[19] Majaranta P, MacKenzie S, Aula A and Räihä K-J 2006 Effects of feedback and dwell time on eye typing speed and accuracy *Univ. Access. Inf. Soc.* **5** 199–208

[20] Brunner P, Ritaccio A L, Emrich J F, Bischof H and Schalk G 2011 Rapid communication with a 'P300' matrix speller using electrocorticographic signals (ECoG) *Front. Neurosci.* **5** 5

[21] Usakli A B, Gurkan S, Aloise F, Vecchiato G and Babiloni F 2010 On the use of electrooculogram for efficient human computer interfaces *Comput. Intell. Neurosci.* **2010** 135629

[22] Lalor E, Kelly S, Finucane C, Burke R, Smith R, Reilly R and McDarby G 2005 Steady-state VEP-based brain–computer interface control in an immersive 3D gaming environment *EURASIP J. Appl. Signal Proc.* **19** 3156

[23] Schreuder M, Blankertz B and Tangermann M 2010 A new auditory multi-class brain–computer interface paradigm: spatial hearing as an informative cue *PLoS ONE* **5** e9813

[24] Höhne J, Schreuder M, Blankertz B and Tangermann M 2010 Two-dimensional auditory P300 speller with predictive text system *Conf. Proc. IEEE Eng. Med. Biol. Soc.* **1** 4185–8

[25] Klobassa D S, Vaughan T M, Brunner P, Schwartz N E, Wolpaw J R, Neuper C and Sellers E W 2009 Toward a high-throughput auditory P300-based brain–computer interface *Clin. Neurophysiol.* **120** 1252–61

[26] Brouwer A-M and van Erp J B F 2010 A tactile P300 brain–computer interface *Front. Neurosci.* **4** 036003

[27] Polich J, Ellerson P C and Cohen J 1996 P300, stimulus intensity, modality and probability *Int. J. Psychophysiol.* **23** 55–62

[28] Comerchero M D and Polich J 1999 P3a and P3b from typical auditory and visual stimuli *Clin. Neurophysiol.* **110** 24–30

[29] Aloise F, Lasorsa I, Schettini F, Brouwer A, Mattila D, Babiloni F, Salinari S, Marciani M and Cincotti F 2007 Multimodal stimulation for a P300-based BCI *Int. J. Bioelectromagn.* **9** 128–30

[30] Sellers E W, Krusienski D J, McFarland D J and Wolpaw J R 2007 *Toward Brain–Computer Interfacing* Non-invasive brain–computer interface research at the Wadsworth Center (Cambridge, MA: MIT Press) pp 31–42

[31] Blankertz B, Krauledat M, Dornhege G, Williamson J, Murray-Smith R and Müller K-R 2007 A note on brain actuated spelling with the Berlin Brain–Computer Interface *Universal Access in HCI, Part II, HCII 2007* ser. LNCS vol 4555 ed C Stephanidis (Berlin: Springer) pp 759–768

[32] Williamson J, Murray-Smith R, Blankertz B, Krauledat M and Müller K-R 2009 Designing for uncertain, asymmetric control: interaction design for brain–computer interfaces *Int. J. Hum. Comput. Stud.* **67** 827–41

[33] Saenz M, Buracas G T and Boynton G M 2002 Global effects of feature-based attention in human visual cortex *Nat. Neurosci.* **5** 631–2

[34] Treisman A and Gelade G 1980 A feature-integration theory of attention *Cogn. Psychol.* **12** 97–136

[35] Carter R C 1982 Visual search with color *J. Exp. Psychol. Hum. Percept. Perform.* **8** 127–36

[36] Blankertz B, Lemm S, Treder M S, Haufe S and Müller K-R 2011 Single-trial analysis and classification of ERP components—a tutorial *Neuroimage* **56** 814–25

[37] Treder M S, Schmidt N M and Blankertz B 2010 Towards gaze-independent visual brain–computer interfaces *Front. Comput. Neurosci. Conference abstract: Bernstein Conference on Computational Neuroscience* 2010

[38] Ishihara S 1919 *Tests for colour-blindness* (Tokyo, Japan: Hongo Harukicho)

[39] Michelson A A 1927 *Studies in Optics* (Chicago, Il: University of Chicago)

[40] Venthur B, Scholler S, Williamson J, Dähne S, Treder M S, Kramarek M T, Müller K-R and Blankertz B 2010 Pyff—a pythonic framework for feedback applications and stimulus presentation in neuroscience *Front. Neurosci.* **4** 179

[41] Straw A D 2008 Vision Egg: an open-source library for realtime visual stimulus generation *Front. Neuroinform.* **2** 4

[42] Liu Y, Zhou Z and Hu D 2011 Gaze independent brain–computer speller with covert visual search tasks *Clin. Neurophysiol.* **122** 1127–36

[43] Krusienski D, Sellers E W, McFarland D J, Vaughan T M and Wolpaw J R 2008 Toward enhanced P300 speller performance *J. Neurosci. Methods* **167** 15–21

[44] Draper N and Smith H 1981 *Applied Regression Analysis (Wiley Series in Probability and Mathematical Statistics)* 2nd ed (New York: Wiley) pp 307–12

[45] Treder M S and Blankertz B 2010 '(C)overt attention and visual speller design,' Poster and talk at 4th Intl BCI Meeting in Asilomar, CA

[46] Palmer S E 1999 *Vision Science: Photons to Phenomenology* ed S E Palmer (Cambridge, MA: MIT Press)

[47] Schreuder M, Höhne J, Treder M S, Blankertz B and Tangermann M 2011 Performance optimization of ERP-based BCIs using dynamic stopping *Conf. Proc. IEEE Eng. Med. Biol. Soc.* at press

[48] Hubel D H and Wiesel T N 1968 Receptive fields and functional architecture of monkey striate cortex *J. Physiol.* **195** 215–43

[49] Ferrez P and Millán J 2008 Error-related EEG potentials generated during simulated brain–computer interaction *IEEE Trans. Biomed. Eng.* **55** 923–9

[50] Spüler M 2010 Online Erkennung von Fehlerpotentialen zur Fehlerkorrektur bei einem P300 Brain–Computer Interface *Diploma Thesis* Eberhard Karls Universität Tübingen

[51] Seno B D, Matteucci M and Mainardi L 2010 Online detection of P300 and error potentials in a BCI speller *Comput. Intell. Neurosci.* **2010** 307254

[52] Schmidt N M, Blankertz B and Treder M S 2011 Online detection of error-related potentials increases information

throughput in a brain–computer interface, *Neurosci. Lett.* **500** e19–20

[53] Sannelli C, Dickhaus T, Halder S, Hammer E M, Müller K-R and Blankertz B 2010 On optimal channel configurations for SMR-based brain–computer interfaces *Brain Topogr.* **23** 186–93

[54] Acqualagna L, Treder M S, Schreuder M and Blankertz B 2010 A novel brain–computer interface based on the rapid serial visual presentation paradigm *Conf. Proc. IEEE Eng. Med. Biol. Soc.* **1** 2686–9

[55] Aricò P, Aloise F, Schettini F, Riccio A, Salinari S, Babiloni F, Mattia D and Cincotti F 2010 GeoSpell: an alternative P300 based speller interface towards no eye gaze required *Proc. on the TOBI Workshop II*

[56] Sutter E E 1992 The brain response interface: communication through visually-induced electrical brain responses *J. Microcomp. App.* **15** 31–45

[57] Kelly S, Lalor E, Reilly R and Foxe J 2005 Visual spatial attention tracking using high-density SSVEP data for independent brain–computer communication *IEEE Trans. Neural Syst. Rehabil. Eng.* **13** 172–8

[58] Allison B, McFarland D, Schalk G, Zheng S, Jackson M and Wolpaw J 2008 Towards an independent brain–computer interface using steady state visual evoked potentials *Clin. Neurophysiol.* **119** 399–408

[59] Müller M M, Andersen S, Trujillo N J, Valdes-Sosa P, Malinowski P and Hillyard S A 2006 Feature-selective attention enhances color signals in early visual areas of the human brain *Proc. Natl Acad. Sci. USA* **103** 14250–4

[60] Zhang D, Maye A, Gao X, Hong B, Engel A K and Gao S 2010 An independent brain–computer interface using covert non-spatial visual selective attention *J. Neural. Eng.* **7** 16010

[61] Bahramisharif A, van Gerven M, Heskes T and Jensen O 2010 Covert attention allows for continuous control of brain–computer interfaces *Eur. J. Neurosci.* **31** 1501–8

[62] van Gerven M and Jensen O 2009 Attention modulations of posterior alpha as a control signal for two-dimensional brain–computer interfaces *J. Neurosci. Methods* **179** 78–84

[63] van Gerven M, Bahramisharif A, Heskes T and Jensen O 2009 Selecting features for BCI control based on a covert spatial attention paradigm *Neural Netw.* **22** 1271–7

[64] Schmidt N M, Blankertz B and Treder M S 2010 Alpha-modulation induced by covert attention shifts as a new input modality for EEG-based BCIs *Proc. 2010 IEEE Conf. on Systems, Man and Cybernetics (SMC 2010)* pp 481–487

[65] Treder M S, Bahramisharif A, Schmidt N M, van Gerven M and Blankertz B 2011 Brain–computer interfacing using modulations of alpha activity induced by covert shifts of attention *J. Neuroeng. Rehabil.* **8** 24

[66] Kelly S P, Lalor E C, Reilly R B and Foxe J J 2005 Independent brain computer interface control using visual spatial attention-dependent modulations of parieto-occipital alpha *Proc. 2nd Int. IEEE EMBS Conf. on Neural Engineering, Arlington, VA* pp 667–70