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Comparing tactile and visual gaze-independent brain–computer interfaces in patients with amyotrophic lateral sclerosis and healthy users

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H I G H L I G H T S

- ALS patients with mild to moderate disabilities can control a visual gaze-independent BCI spelling system.
- The visual Hex-o-Spell outperforms the tactile speller in both healthy participants and ALS patients.
- Subjective assessment shows that attending to visual stimuli is easier than attending to tactile stimuli, even if the stimuli are in the peripheral visual field.

A B S T R A C T

Objective: Brain–computer interfaces (BCI) tested in patients often are gaze-dependent, while these intended users could possibly lose the ability to focus their gaze. Therefore, a visual and a tactile gaze-independent spelling system were investigated.
Methods: Five patients with amyotrophic lateral sclerosis (ALS) tested a visual Hex-o-Spell and a tactile speller. Six healthy participants were also included, mainly to evaluate the tactile stimulators.
Results: A significant attentional modulation was seen in the P300 for the Hex-o-Spell and in the N2 for the tactile speller. Average on-line classification performance for selecting a step in the speller was above chance level (17%) for both spellers. However, average performance was higher for the Hex-o-Spell (88% and 85% for healthy participants and patients, respectively) than for the tactile speller (56% and 53%, respectively). Likewise, bitrates were higher for the Hex-o-Spell compared with the tactile speller, and in the subjective usability a preference for the Hex-o-Spell was found.
Conclusions: The Hex-o-Spell outperformed the tactile speller in classification performance, bit rate and subjective usability.
Significance: This is the first study showing the possible use of tactile and visual gaze-independent BCI spelling systems by ALS patients with mild to moderate disabilities.

1. Introduction

The most investigated brain–computer interface (BCI) for communication is the visual speller which uses flashing rows and columns (Farwell and Donchin, 1988). Participants pay attention to a symbol that they want to select. Every symbol is characterized by its own unique sequence of flashes. The flash of an attended symbol yields a different electroencephalographic (EEG) response compared with flashes of other symbols. By aggregating information over a sequence of flashes, the BCI can detect the desired symbol. To get highest performance, participants need to direct their gaze to the desired symbol: a covert version of this speller, in which users are not allowed to look at the symbol, but must keep their gaze fixated on the center of the display, has much lower performance (Brunner et al., 2010; Treder and Blankertz, 2010). This

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means that patients whose vision or gaze control is impaired, will have significantly reduced performance, or cannot use this system at all. Patients with amyotrophic lateral sclerosis (ALS), a progressive neurodegenerative disease affecting the motor neurons, have a high risk of becoming locked-in. Furthermore, many of these patients may develop oculomotor control deficits. Therefore, they can probably not use systems that depend on eye gaze. Recently, Riccio et al. (2012) systematically reviewed the available systems that could be used independent of eye gaze in the auditory, tactile and visual domain. Only two of the 34 included articles tested their system with end-users (ALS patients). Both were auditory BCIs (Sellers and Donchin, 2006; Kübler et al., 2009). To the best of our knowledge, no studies have been conducted with visual or tactile eye-gaze independent BCIs in ALS patients.

Several tactile BCI systems have been tested successfully in healthy subjects. A first BCI based on tactile stimulation focussed on steady-state somatosensory potentials (Müller-Putz et al., 2006). Later, transient ERP responses to tactile stimulation of the trunk (Brouwer and van Erp, 2010; Thurlings et al., 2011, 2012) and fingers have been used as well (Severens et al., 2013). Recently, in healthy subjects we showed that a tactile speller performed similar to a gaze-independent visual speller (Van der Waal et al., 2012). In the tactile speller, stimulus events are short mechanical taps against the fingertips. Initially, each finger corresponds to a number of letters. After the selection of a subset of letters, these letters are distributed over the fingers. Then a single letter can be selected. Thus, spelling a letter is a two-step procedure. The gaze-independent visual speller that was used in the comparison was the Hex-o-Spell. This speller was first introduced by Treder and Blankertz (2010) and was later evaluated in an online setting (Treder et al., 2011). In this Hex-o-Spell, letters are divided over six circles on the screen. Covert attention is used to select the desired circles. Stimulus events are an intensification of a circle and the including symbols. Again the selection of a letter occurs in two steps: first a circle of letters is selected; second the remaining letters are distributed over the circles and an individual letter can be selected. Both the tactile speller and Hex-o-Spell are promising for patients that cannot control eye gaze.

The number of studies in which end-users evaluate the BCI is limited. Although some studies that do include end-users report similar performance compared with able-bodied subjects, (Sellers and Donchin, 2006; Nijboer et al., 2008b; Pires et al., 2012), others report lower performance in end-users (Piccione et al., 2006; Kübler et al., 2009; Ortner et al., 2011). Evaluations with end-users are necessary to assess not only the performance of BCI systems, but also the usability in these end-users.

In the present paper, the performance of the tactile speller and Hex-o-Spell were compared. Participants included a group of healthy subjects and a group of ALS patients. Because this is the first study on gaze-independent BCIs using tactile and visual stimuli that includes patients we selected patients with mild to moderate disabilities. The healthy group was included mainly for testing newly developed tactile stimulators. Furthermore, for both systems the subjective usability in terms of need for support, training and complexity was assessed and compared.

2. Methods

2.1. Participants

Eleven volunteers participated in this study: six healthy subjects (mean age 20 year (SD 0.4), 4 female) and five individuals with ALS. Inclusion criteria were a diagnosis of typical ALS and a duration of the illness of less than 3 years. Exclusion criteria were other neurological disorders and inability to understand and carry out the test instructions. All participants gave written informed consent before the start of the experiment. The experiment was approved by the ethical committee of the faculty of social sciences at the Radboud University Nijmegen, and the committee of human research Arnhem – Nijmegen. All participants were tested at the BCI lab of the Radboud University Nijmegen. Patient characteristics are included in Table 1.

2.2. Materials

EEG was recorded with 64 sintered Ag/AgCl active electrodes, referenced to the mean of all electrodes. Signals were amplified using a Biosemi activeTwo system. The sampling rate of the EEG data was 2048 Hz. The amplifier includes an anti-aliasing filter at 410 Hz (5th order sinc filter).

For an application for end-users it is important that the tactile stimulators can be attached to the body without the need for active holding. The stimulators used in the previous tactile speller study (Van der Waal et al., 2012), did not meet these requirements. Therefore, new stimulators were manufactured, and these were tested in the current study. Six custom made stimulators based on solenoids (Zonhen electric appliances China) were used (see Fig. 1). The stimulators were attached to the tips of the thumb, middle finger and little finger on each hand. Each stimulator contains a metal pin (diameter 2 mm) that could be pushed out over a distance of 0.7 mm. Visual stimuli were presented on a 17'' TFT monitor, with a resolution of 800 $\times$ 600 pixels and a refresh rate of 60 Hz.

Both spellers were implemented in BrainStream (www.brainstream.nu), a MATLAB (The MathWorks, Natick, MA, USA) based

Table 1
Background data of participants with ALS.

Patient	Age	Sex	ALS type	Time since diagnosis	ALSFRS-R
A	36	M	Spinal	29 months	Unknown[a]
B	50	F	Bulbar	15 months	43
C	30	M	Spinal	7 months	27
D	56	F	Bulbar	3 months	45
E	23	F	Spinal	21 months	24

ALSFRS-R ALS functional rating score revised (Cedarbaum et al., 1999), which rates the physical impairment on a scale from 0 (maximally disabled) to 48 (not impaired).
[a] Because the ALSFRS-R was not assessed in the period of the BCI experiment, the score is reported as unknown.

Fig. 1. Tactile stimulators attached to the thumb, middle finger and little finger of the left hand. The inset shows an enlarged view of one stimulator with the pin protruding from the stimulator.