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REVIEW ARTICLE

Human visual skills for brain-computer interface use: a tutorial

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ABSTRACT

Background and objectives: Many brain-computer interfaces (BCIs) for people with severe disabilities present stimuli in the visual modality with little consideration of the visual skills required for successful use. The primary objective of this tutorial is to present researchers and clinical professionals with basic information about the visual skills needed for functional use of visual BCIs, and to offer modifications that would render BCI technology more accessible for persons with vision impairments.
Methods: First, we provide a background on BCIs that rely on a visual interface. We then describe the visual skills required for BCI technologies that are used for augmentative and alternative communication (AAC), as well as common eye conditions or impairments that can impact the user's performance. We summarize screening tools that can be administered by the non-eye care professional in a research or clinical setting, as well as the role of the eye care professional. Finally, we explore potential BCI design modifications to compensate for identified functional impairments. Information was generated from literature review and the clinical experience of vision experts.
Results and conclusions: This in-depth description culminates in foundational information about visual skills and functional visual impairments that affect the design and use of visual interfaces for BCI technologies. The visual interface is a critical component of successful BCI systems. We can determine a BCI system for potential users with visual impairments and design BCI visual interfaces based on sound anatomical and physiological visual clinical science.

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Brain-computer interface; vision; visual impairments; severe disabilities; assistive technology

➤ **IMPLICATIONS FOR REHABILITATION**

- As brain-computer interfaces (BCIs) become possible access methods for people with severe motor impairments, it is critical that clinicians have a basic knowledge of the visual skills necessary for use of visual BCI interfaces.
- Rehabilitation providers must have a knowledge of objectively gathering information regarding a potential BCI user's functional visual skills.
- Rehabilitation providers must understand how to modify BCI visual interfaces for the potential user with visual impairments.
- Rehabilitation scientists should understand the visual demands of BCIs as they develop and evaluate these new access methods.

Introduction

Brain-computer interface (BCI) systems offer a promising new platform for assistive technologies (AT), including access tools for augmentative and alternative communication (AAC), computer use, mobility, prosthetic limb control, motor and cognitive rehabilitation, electronic aids to daily living, and artistic expression, among others [1–3]. With BCI, AT control is achieved *via* users' brain signals, bypassing impaired motor systems and providing the potential for control by individuals with locked-in syndrome and other forms of severe physical disability.

Brain signals for BCI are acquired either noninvasively (often with electroencephalography [EEG], using electrodes held against the scalp by a cap or headset), or invasively (with electrodes that have been surgically implanted on the surface of the brain or into the cortex). There are two primary ways for a BCI user to produce brain signals for system control. Many BCI systems require the user to attend and respond to external stimuli, analogous to activating a switch to select a desired item *via* single-switch scanning in traditional AAC software. Others allow the user to control a cursor in one or two dimensions, typically with motor imagery (e.g., imagine moving the left or right hand to move the cursor left or right) [4]. BCI algorithms are trained to recognize and interpret each user's unique brain responses, similar to the way eye trackers are calibrated for AAC control.

Because of the potential benefits for individuals with severe speech and physical impairments (SSPI), numerous BCI systems have been designed for AAC; we refer to these as AAC-BCIs. Both invasive [5,6] and non-invasive [7–10] AAC-BCIs have been tested by people with SSPI, and several research groups have reported on long-term, independent home use of these systems for

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Supplemental data for this article can be accessed here.

communication [5,6,8]. It is possible that future BCI systems may allow the direct, real-time translation of thoughts into speech (see [11,12] for preliminary investigations), but current AAC-BCIs function in a similar manner to traditional AAC access methods, requiring the user to select or generate messages by controlling a software interface [13].

As with all AT systems, BCIs involve input to and output from the user. In single-switch scanning for control of an AAC interface, for example, inputs to the user include the letters or other stimuli in the grid, the position of the scanning indicator on the screen (i.e., the currently highlighted group or item), and the current state of the message window (e.g., a partially-typed word). Based on these inputs, the user either does or does not produce an output in the form of a switch activation for selection of the currently highlighted item. If the user struggles to see the stimuli or track the scanning indicator, she may have difficulty producing outputs to achieve her desired actions.

A user may receive similar inputs from a visual AAC-BCI system, and produce similar outputs (one brain signal to indicate a desired selection and a different, or absent, brain signal to indicate a non-targeted stimulus). However, many AAC-BCIs demonstrate a crucial difference from other AAC access methods: the user's ability to produce the needed output is dependent on the input. A person using single-switch scanning is able to activate his switch at any time, regardless of what is happening in the AAC interface. By contrast, the brain signals required to operate AAC-BCIs relying on external stimuli occur only in reaction to those external stimuli.

As in many systems, a principle of "garbage in, garbage out" applies. Visual skills, particularly the ability to see, focus on, and distinguish among stimuli, are essential to ensure that users are receiving the expected inputs from a visual BCI, and are thus able to produce useful outputs. Many potential BCI users with SSPI present with concomitant visual impairments, eye movement disorders, or eye diseases [14–16], which may affect these important visual skills and thus the ability to use a visual BCI.

There has been little discussion in the literature about the importance of vision for BCI performance, despite the fact that most BCI user interfaces rely on visual stimuli. Visual deficits may contribute to some users' poor BCI performance [9], a phenomenon sometimes referred to as "BCI illiteracy". It has been suggested that what has been called illiteracy may, in fact, reflect a failure to properly design or adapt a system to a particular user's needs and abilities [17]. After all, a person with vision impairment may be unable to read printed words, but may consume great volumes of literature with the appropriate technology (i.e., Braille or audiobooks). It would be inappropriate and inaccurate to call such a person "illiterate". The same logic applies to many potential BCI users who have not been provided with technology suited to their skills. Identification of visual impairments and implementation of corrective or compensatory measures may represent important steps towards successful BCI use for some individuals.

As AAC-BCIs move towards clinical implementation for individuals with SSPI, it is critical that both clinicians and researchers have a basic knowledge of the visual skills necessary for use of visual BCI interfaces, as well as common eye conditions or impairments that may affect performance. In addition, knowledge of how to objectively gather information regarding a potential user's functional visual skills may facilitate an informed approach to the user-technology match [18].

We begin this tutorial with an overview of visual AAC-BCI interfaces and the relatively scant available literature on the relationship between visual skills and BCI performance. Next, we explore visual skills frequently impaired in people with SSPI and how such deficits may affect BCI use. We also propose simple visual screening techniques and discuss the role of vision professionals in providing further diagnosis and therapeutic interventions. We conclude with suggested design considerations and interface modification options, incorporating principles of universal design which have been used to make the internet more accessible to individuals with visual impairments. We focus primarily on AAC-BCIs since our laboratory specializes in this area, but the recommendations provided are applicable to any BCI using a visual interface.

Visual interfaces for AAC-BCIs

Many AAC-BCIs present visual stimuli and/or provide visual feedback for letter selection and message generation, with layout and interface features often influenced by the type of brain signal acquired for system control [19]. The P300 Speller, a frequently investigated non-invasive AAC-BCI, relies on external stimuli to provoke specific brain responses in the user. The speller presents letters and other targets in a matrix layout on a computer screen [8,20]. Subsets of letters (or individual letters) quickly flash or intensify at random, and the user attends to a desired target and notes each time it flashes. Attention to these flashes elicits a P300 event-related potential (ERP), a brain response that results directly from observation of a novel stimulus (in this case, the flashing target letter). The P300 ERP also has been used with rapid serial visual presentation (RSVP) interfaces, which present a stream of characters in a consistent location on a computer screen [7,21–23]. The user watches the stream and notes the appearance of a desired target letter, which serves as the novel stimulus for eliciting the P300 ERP to signal the user's intent. For further information on RSVP spellers, readers are directed to a literature review by Lees et al. [24].

Visual evoked potentials (VEPs) are also commonly used as control signals for non-invasive AAC-BCIs [25,26]. Like the P300 ERP, VEPs are elicited by external stimuli. When multiple lights or images flicker at different frequencies, each elicits a different response in the visual cortex. These different VEP responses can be distinguished by a well-trained BCI algorithm, so that the detected response indicates the user's intended target. In VEP-based AAC-BCIs, letters may be presented on a monitor and associated with stimuli flashing at various frequencies or in coded patterns, or the letters themselves may flash [27].

Some AAC-BCIs require the user to perform specific mental tasks, such as motor imagery, to generate brain signals for system control, instead of reacting to external stimuli. In one non-invasive visual AAC-BCI, letters or groups of letters are arranged in a circle on a computer screen, with an arrow-shaped cursor in the centre. The user imagines moving her right hand to advance the cursor clockwise until it points at her desired target, then imagines moving her left hand to select that target [28]. In one invasive AAC-BCI, users gain full two-dimensional cursor control *via* imagined hand and arm movements, allowing them to type on an onscreen keyboard as if they were moving a physical mouse [5]. Another invasive system requires the user to produce "brain clicks" with motor imagery for control of a visual automatic scanning interface [6].

There are numerous variations on the general visual BCI interface categories described above. A variety of matrix sizes, flash durations and patterns, stimulus colour combinations, and alternative stimuli have been explored as modifications of the P300 matrix speller interface [29–32]. One alternative to flashing letters on the matrix is the face speller, in which each character changes to a human face during each flash instead of simply changing colour or intensity. Guger, Ortner, Dimov & Allison [33] showed that, for healthy volunteers, flashing faces on the P300 speller increased the selection performance to much higher speeds compared to more traditional approaches. Additionally, stimuli may change colour or move around the screen to provide visual cues for aiding selection [34]. To reduce the number of stimuli offered for an initial selection, letters or other stimuli may be presented in a branching-tree format in which the user first selects one of two (or more) groups of letters, after which the letters in that group are divided into smaller groups or individual letters for further selection [10,25]. Researchers have proposed icon stimuli as alternatives to letters for individuals with impaired literacy skills or for quick communication regarding everyday needs which may increase visual demands [35]. For example, black-and-white icons have been compared to letter presentations, resulting in longer reaction time in a visual search task compared to letters [36].

Visual skills and visual BCI performance

Researchers have suggested that impaired visual skills may be a factor in poor BCI performance [9], though this has not been explicitly investigated. Eye movement, or ocular motility, has received more attention than other visual skills in the BCI literature. Several studies have identified eye movement as an important skill for successful visual BCI use [37]. Others have proposed "gaze independent" systems that rely on covert attention.

Overt visual attention requires the ability to move the eyes and direct gaze at a target, while covert attention involves attending to an object without gazing at it directly. The role of overt attention in letter selection for AAC-BCIs based on external stimuli is still somewhat unclear. In a recent experiment assessing P300 matrix speller performance in healthy volunteers, subjects were instructed to either look directly at a letter on the screen with overt attention, or look at a fixation cross and attend to the letter with covert attention [37]. Spelling performance was significantly better when participants visually attended to the letter to be typed *via* overt attention. However, other studies have suggested that P300 spelling performance may still be comparable using covert attention [38].

Peters et al. [34] explored the effects of simulated visual acuity and ocular motility impairments on healthy volunteers' performance with a VEP-based speller. The speller was designed with visual impairments in mind, and featured high contrast ratios and large sans-serif font for letter presentation. Simulated visual acuity impairment of 20/200 (equivalent to the U.S. definition of legal blindness) had no significant effect on typing accuracy compared to an unimpaired condition. Simulated ocular motility impairment made the system unusable for many participants, though a small group (6/37) could type with high accuracy.

Visual impairments in BCI user populations

There are populations of individuals with SSPI for whom BCI technology may be particularly beneficial, especially those with locked-in syndrome (LIS), neuromuscular disorders such as amyotrophic lateral sclerosis (ALS) or spinal muscular atrophy, brainstem stroke, or spinal cord injury [3,29,39]. Other target user populations include individuals recovering from strokes [40] and those with cerebral palsy [41] or disorders of consciousness [42,43]. Research on the co-occurrence of visual impairments with conditions causing SSPI is limited, perhaps due to the difficulty of assessing visual skills in individuals with limited communication and mobility. A list of visual impairments known to be associated with LIS, ALS, and cerebral palsy is presented in Table 1. These visual impairments, their prevalence among people with SSPI, and their potential effects on BCI use will be discussed in detail below.

Table 1. Visual impairments reported in clinical populations who present with SSPI.

Clinical population	Functional vision impairment
Locked-in syndrome (LIS)	Reduced visual acuity [15] Nystagmus [15] Abnormal pupillary response [15] Reduced eyelid function [15] Photophobia [15] Reduced ocular motility [15] Diplopia [15] Abnormal visual field [15]
Amyotrophic lateral sclerosis (ALS)	Reduced visual acuity [16] Nystagmus [55] Reduced eye lid function [16] Reduced ocular motility [16,55]
Cerebral palsy (CP)[a]	Reduced visual acuity [50–52] Cataracts [50–52] Nystagmus [50] Reduced ocular motility [14,50,59] Strabismus [59,60] Abnormal visual field [50,52,59] Reduced visual perceptual skills [70]

[a]The majority of evidence is from studies on children with cerebral palsy, but can be presumed to impact visual skills in adulthood.

Visual skills and visual impairments relevant to BCI use

The following visual skills have been identified as integral to effective use of AT that requires visual interaction, and may therefore be applicable to visual BCI technologies: visual fixation, visual acuity, pursuit and saccadic movements, binocular vison, field of vision, and perceptual abilities [44]. An impairment in any of these visual skills can potentially reduce the user's performance with a visually based BCI system. Below we will define terminology and illustrate the potential impact of these visual skills and associated impairments on BCI performance. Visual skills, as well as related conditions and impairments and suggested interface modifications, are summarized in Table 2.

Visual acuity

Visual acuity refers to clarity or sharpness of vision [45]. Impaired visual acuity is common in the general population [46]. Although research on the prevalence of visual impairments among individuals with SSPI is limited, conditions which are common in the general population, particularly among older adults, may be assumed to be common among potential BCI users. A study of visual impairments in people with ALS found that these individuals demonstrated reduced visual acuity compared to controls after accounting for age [16]. Assessment of a small sample of individuals with LIS revealed a mean visual acuity (with best correction) of 20/60 [15]. As a point of reference, the International Statistical Classification of Diseases and Related Health Problems (ICD-10) [47] classifies visual acuity of 20/70 or worse as a moderate visual impairment. We will discuss some common aetiologies of impaired visual acuity below.

Refractive errors are the result of an abnormality in the shape of the eyeball. Depending upon the maladaptive shape, light

Table 2. Summary of visual skills important for visual BCI use, associated conditions and impairments, and suggested BCI interface modifications.

Visual skill	Definition	Associated conditions and impairments	Suggested interface modifications
Visual acuity	Clarity or sharpness of vision	Refractive error Cataract Retinal disease Nystagmus Dry eye/exposure keratitis	Increase stimulus size Increase contrast between stimuli and background
Visual fixation	Ability to accurately sustain gaze on an object	Nystagmus Poor binocular skills	Reduce number of stimuli Increase spacing of stimuli Eliminate use of dynamic stimuli Increase stimulus size
Pupillary function	Response of the pupils to light in the environment	Miosis Mydriasis	Reduce luminance to accommodate photophobia Increase luminance to improve acuity
Eyelid function	Ability to voluntarily open and close the eyelid	Ptosis Lagophthalmos	Arrange stimuli to accommodate available field of view Reduce luminance to accommodate photophobia
Ocular motility	Ability to move the eyes and track moving objects	Extraocular muscle dysfunction Impaired pursuit eye movement Impaired saccadic eye movement	Arrange stimuli to accommodate reduced range of motion Slow the rate of moving stimuli Have stimuli move in finite, predictable areas Increase interstimulus intervals
Binocular vision	Ability to appropriately fuse the separate images perceived by each eye into a single composite image	Strabismus Diplopia High heterophoria	Interface modifications are unlikely to be helpful Refer to neuro-optometry for recommendation of prisms or other interventions
Field of vision	Ability to view the surrounding environment while fixating the eyes straight ahead	Retinal disease Optic nerve disease Hemianopia Scotoma	Arrange stimuli to accommodate available field of view (reduce stimulus size, if necessary) Have stimuli move in finite, predictable areas within available field of view Increase contrast between stimuli and background
Colour vision	Ability to discriminate among colours	Colour vision deficiency	Avoid poor colour combinations Increase luminance Increase contrast between stimuli and background
Visual perception	Ability to acquire and understand visual information from the environment	Visual perceptual dysfunction	Use simple, familiar stimuli Avoid visual distractions and overcrowding Allow additional time to process visual information

entering the eye is misfocused either in front of the retina (myopia/nearsightedness), or behind the retina (hyperopia/farsightedness), or both in front of and behind the retina (astigmatism) [48]. These refractive errors are present in approximately half of the general population over twenty years old [46] and are commonly corrected by prescription lenses or contacts.

Cataracts are the result of a clouding of the crystalline lens of one or both eyes. This increased opacity of the lens results in blurred vision [45]. Cataracts are part of the normal aging process and are found in 17.2% of Americans over 40 years of age [49]. Although limited research is available for adults with cerebral palsy, paediatric literature reveals an increase for both refractive error and cataracts for this population when compared to their typically developing peer group [50–52].

Other pathological conditions that may contribute to reduced visual acuity include retinal diseases (such as macular degeneration and diabetic retinopathy) [53], nystagmus, diplopia [48], dry eye, and exposure keratitis. These conditions will be discussed further below.

It is worth noting that given medical fragility, difficulty with transportation, communication impairments, or insurance issues, potential BCI users may not receive regular, complete eye exams or updates to their prescription lenses. Thus, they may be less likely than the general population to have adequate correction for reduced visual acuity.

Visual acuity plays a significant role in the ability to view and interact with a visually based interface. Depending upon the size, spacing, level of detail, and contrast of the targets presented on a BCI interface, a reduction in the user's visual acuity may interfere with their ability to distinguish and identify targets or to read feedback messages and instructions on the interface.

Visual fixation

Visual fixation refers to the ability to sustain gaze on a stationary object [45]. Visual fixation is a crucial skill to allow for the cognitive processing of visual information [54]. Loss of visual fixation is often associated with nystagmus, a condition involving involuntary, rhythmically oscillating eye movements that typically occurs as a result of diseases of the central nervous system [45]. Nystagmus can contribute to blurred vision, nausea, and visual confusion [48] and has been observed in individuals with LIS [15] and ALS [55] and in children with cerebral palsy [50]. The presence of nystagmus may reduce a BCI user's ability to adequately fixate on a target for adequate calibration, or may reduce visual acuity when discriminating among multiple stimuli on a computer interface.

Pupillary function

Pupillary function refers to the response of the pupils to light in the environment. Healthy pupils constrict under greater light intensity and dilate under lower light intensity to regulate the amount of light entering the eye. Some people with SSPI may experience disorders of pupillary function, including miosis or mydriasis. Miosis is the excessive constriction of the pupil, which can cause reduced visual acuity due to insufficient light reaching the retina. Conversely, mydriasis is the abnormal dilation of the pupil [45] which can manifest as photophobia, an abnormal sensitivity to otherwise normal lighting conditions. Both miosis and mydriasis can occur as side effects of medications often administered to those with SSPI, such as muscle relaxants or narcotics [56]. Graber et al. [15] observed an abnormal pupillary response in 22% of their sample of individuals with LIS. This inability to regulate the amount of light which enters the eye due to abnormal pupillary function may decrease tolerance for varying degrees of luminance emitted by flashing on-screen stimuli or LED lights.

Eyelid function

Eyelid function refers to the ability to voluntarily and completely open or close the eyelid. Ptosis, a drooping of the upper eyelid, may cover all or part of the pupil and interfere with vision. A related condition is lagopthalmos, defined as reduced eyelid closure during blinks. Both ptosis and lagopthalmos can inhibit proper lubrication of the ocular surface, potentially resulting in dry eye or exposure keratitis (an inflammation of the corneal surface) [45]. Dry eye and exposure keratitis can lead to discomfort or photophobia, and in extreme cases may cause permanent damage to the cornea, which can affect visual acuity. Ptosis is common among individuals with ALS [16], and may also be caused by other neuromuscular diseases, stroke, tumour, nerve damage, or congenital conditions [15,16,57,58]. Exposure keratitis was found in the majority of participants with LIS evaluated by Graber et al. [15]. Ptosis may reduce field of vision for viewing a BCI interface, specifically the user's ability to see targets in areas obscured by the drooped lid. Photophobia or discomfort due to reduced eyelid closure may make it difficult for a user to look at a visual BCI interface, particularly at bright stimuli such as the flashing LEDs used by some VEP BCIs, or to use the interface for long periods of time.

Ocular motility

Ocular motility refers broadly to the function of the six extraocular muscles and their effect on eye movements [45]. Reduced ocular motility control is commonly observed in people with LIS [15] and ALS [16]. Although limited research is available for adults with cerebral palsy, paediatric literature reveals a significant portion of this population display an oculomotor dysfunction [14,50,59]. An impairment involving the extraocular muscles may limit range of motion for horizontal, vertical, or rotational eye movements. Specific types of eye movement, including pursuit and saccadic, may also be impaired. These eye movements are described further below.

Pursuit eye movement

Pursuit eye movement is the ability to produce smooth, rhythmic motion of both eyes simultaneously while following a moving object. Adequate pursuit movements are required for the user to follow a dynamic target on the interface. Lack of adequate visual pursuit speed or accuracy may result in a poor ability to track moving targets or cursors [45].

Saccadic eye movement

Saccadic eye movements are the quick, simultaneous eye movements necessary for fixation and refixation on targets during reading other visual scanning tasks [45]. Both the quality of coordination and the speed of the user's saccadic movements will affect the efficiency and accuracy of target selection. A reduction in saccadic eye movements may reduce a user's ability to effectively visually scan or read information on a computer interface resulting in potential selection errors.

Binocular vision

Binocular vision is the blending or fusing of the separate images perceived by each eye into one composite image [45]. Binocular vision is dependent upon the synergistic movement of the six extraocular muscles mentioned above. Dysfunction in one or more of these muscles can result in strabismus or high heterophoria, two types of misalignment of the eyes that often affect binocular vision. Strabismus may be congenital, or may be acquired because of disease or trauma. This misalignment may cause diplopia (double vision). Graber et al. [15] observed diplopia in 46% of their sample of people with LIS. In a population-based sample of 106 children diagnosed with cerebral palsy, 55.7% experienced strabismus, [59] and results as high as 70.5% have been found in children with spastic cerebral palsy [60]. Double vision may contribute to visual confusion and decrease the user's ability to distinguish an intended target or read instructions or feedback provided by the interface.

Field of vision

Field of vision is the extent to which the environment is visible while the eyes are fixating straight ahead [45]. An individual with an intact visual field can typically detect stimuli 160 degrees horizontally and 120 degrees vertically [48]. A restriction to any part of the visual field, whether it be in the peripheral or central field, is considered a visual field loss. Several eye conditions that commonly contribute to visual field loss are discussed below.

Retinal diseases such as age-related macular degeneration (AMD) or diabetic retinopathy often present as a central visual field loss. Functionally, these diseases cause scotomas (blind spots) which can obscure the area of the eye with the greatest density of photoreceptors, making reading or the discerning of fine details very difficult or impossible [45]. Although specific statistics are not available for the identified BCI user populations, the prevalence of AMD in the US for those over 40 is 6.5% [61]. Among Americans with diabetes, 28.5% present with diabetic retinopathy [62].

Optic nerve diseases or injuries such as glaucoma [45], optic atrophy [63], tumours [64], or traumatic injury [65] may cause a peripheral field loss. Functionally, a peripheral field loss presents as "tunnel vision", inhibiting awareness (in either or both eyes) of the temporal, inferior and superior peripheral visual fields. If the disease or injury is severe, it can lead to blindness. Paediatric literature reporting on children with cerebral palsy reveals evidence of restricted visual fields resulting from optic atrophy [50].

Hemianopia refers to a loss of vision either to the right or left of midline (essentially blocking half of the world from view), and may result from trauma, stroke, or tumours [45]. A review of paediatric literature reveals a small occurrence (1.4%) of restricted visual fields resulting from hemianopia for children with cerebral palsy [52,59]. Abnormal visual fields were observed in 17% of individuals with LIS assessed by Graber et al. [15].

The presence of abnormal visual fields for a BCI user will interfere with visually based BCI use. Depending upon the location and severity of the visual field loss, there will be a disruption in the user's ability to see all areas of an interface, thereby impeding target awareness and selection accuracy. In addition, the user's ability to adequately track moving targets may be affected, as a dynamic target may be "lost" as it travels through an area of field loss.

Colour vision

Colour vision is the ability to discriminate among colours. Colour discrimination deficiency (commonly known as colour blindness) most commonly occurs with shades of green and red, but a reduced ability to distinguish between other colours may also be affected [45]. Colour discrimination deficiency can occur as a hereditary condition, at a prevalence of 8% for males and 0.4% females in the general population [66], and has been documented in the ALS population [67]. In addition, evidence has been found of reduced colour discrimination for children with spastic cerebral palsy who had more severe motor impairment compared to those with less severe motor impairment [68]. Knowledge that a user experiences a colour discrimination deficiency can be important information as colour is often utilized in visual interfaces to differentiate among targets or provide feedback information (e.g., green = start or correct response, red = stop or error response). Deficits in colour discrimination may lead to confusion and result in selection errors. Alternatively, it may prevent the user from capitalizing on cognitive cues that colour may provide, as in the multi-coloured Shuffle Speller interface [34].

Visual perception

Visual perception is the highly complex procedure of acquiring visual information from the external environment and translating this information into an understanding of one's surroundings [69]. Visual perceptual skills are often described in a hierarchical fashion with the previously discussed visual skills (acuity, ocular motility, visual fields etc.) serving as the foundation for the integration of higher order visual processing skills [54]. As a result, it has been proposed that an impairment in any of these foundational skills may impact the integrity of higher order visual perceptual abilities [54]. In a systematic review evaluating studies of children with cerebral palsy, which included 15 studies between 1990 and 2011, the proportion of visual perception impairment ranged from 40-50% [70]. Research in this area for ALS and LIS populations is limited. An impairment in visual perceptual skills contributes to a decrease in efficient, effective learning and use of BCI technologies. Deficits in visual perception will affect all aspects of processing the visual interface, from understanding the visual tasks required by the BCI system, to selecting targets and confirming correct message formation. For a review of visual perception dysfunction, readers are directed to [54].

The role of optometry/ophthalmology and visual screening in BCI research

A comprehensive visual assessment by an optometrist or ophthalmologist is strongly advised [44] for all potential BCI users to ensure adequate visual skills for successful system use, as well as for perceiving and understanding demonstration videos and instructional materials. However, a complete eye examination may not be a practical option due to medical fragility, transportation difficulty, or insurance limitations. In these cases, although clearly not a replacement for a skilled visual evaluation, standardized visual screenings designed for use by non-eye care professionals may be helpful.

Non-eye care professionals such as occupational therapists [48] and school nurses [71] have historically used standardized tools for early detection and referral to optometry or ophthalmology due to functional visual changes. Many of these standardized screenings may prove to be effective for the BCI population. In addition to providing referral criteria, standardized visual screenings may (1) help determine which BCI visual interface best fits a potential user's skill set (e.g., RSVP vs. matrix speller), (2) assist in establishing and adhering to study inclusion criteria, (3) serve as a guide for interface customization or modification (when appropriate), and (4) provide an objective description of participants' visual skills when disseminating research results.

Standardized visual screening tools

Several existing standardized visual screening tools may be applicable to this complicated population. The Broken Wheel test [72] is a visual acuity test with referral criteria, which does not require typical verbal responses. Rather, it allows for forced-choice responses potentially occurring with eye movements. It can screen for both far and near acuity. The Coma Recovery Scale Revised (CRS-R) [73] provides standardized procedures for administration and response criteria to more uniformly describe the visual fixation or pursuit skills of a user with SSPI. The Northeastern State University College of Optometry (NSUCO) Oculomotor Test [74] provides specific procedural techniques as well as scoring criteria, which allows for uniform description of the accuracy and ability of pursuit and saccade skills for adults and children. Criteria for referral to an eye care professional are specified [72]. Rapid confrontation screening [75] is a standardized screening procedure to detect potential peripheral field defects, as well as criteria for referral.

A specialized screening tool for AAC-BCI research

The Revised BCI Sensory/Cognitive/Communication Screen [76] incorporates tasks from the above standardized tools, and is optimized for use with individuals with SSPI. It was designed to assess the requisite skills for use of visual BCI interfaces, including RSVP Keyboard™ [7], which elicits a P300 response with rapid serial visual presentation of letters, and Shuffle Speller [34,77,78], which involves colour cues, moving targets, and VEP stimulation *via* flashing LED panels. In addition to vision, it includes questions and tasks designed to screen participants' communication, cognitive, literacy, and hearing skills, and to record current medications and motor function. All tasks are modified for people with SSPI, allowing answers to be provided *via* yes/no either responses or eye movements. The tool also incorporates informed consent procedures based on those suggested by Vansteensel et al. [6], presenting yes/no questions to assess participants' comprehension of consent documents.

The vision portion of the screening tool begins with a series of questions to be asked of the participant or a caregiver. These questions cover the date and location of the participant's most recent eye exam, details about corrective lenses, eye medications, vision-related medical diagnoses, and subjective visual problems. Next, participants complete the previously discussed standardized visual screenings to gather objective information on the integrity of basic visual skills. The score sheet for the screening tool is available as online supplemental material.

The role of the eye care professional

If screening results indicate vision impairment, a full vision evaluation is indicated to assess if the user may benefit from further intervention to optimize visual function and visual BCI performance. When available, a referral to a provider specializing in vision disorders related to neurological conditions (a neuro-optometrist or neuro-ophthalmologist) is recommended. The Neuro-Optometric Rehabilitation Association website (www.noravisionrehab.org) may be a good resource for identifying local providers.

There are many interventions that may help improve visual skill performance, including prism lenses, eye lubrication, blink training, and eye exercises. However, such interventions should be recommended only by an eye care professional and should not be attempted by researchers or other clinicians. Once a vision care plan is in place, researchers and clinicians should ensure that it is adhered to during BCI use. For example, care should be taken that the user is wearing current prescription lenses, if applicable. If eye drops have been prescribed, they should be administered as recommended. Other considerations might include positioning fans or heaters so as to avoid drying of the ocular surface, or adjusting room lighting to accommodate photophobia.

Design considerations and suggested modifications for visual BCI interfaces

BCI systems should be accessible to everyone who needs them. Research teams and clinicians may consider a variety of interface modifications to support adequate BCI use for individuals with visual impairment. Principles of universal design should be followed whenever possible, and BCI systems should be customized for each user based on screening results [18,79,80]. See Table 2 for a summary of suggested interface modifications to address specific visual skills.

Follow general ergonomic recommendations for computer users

The monitor should be centred in front of the user, generally at a distance of 50-100 cm with the top of the monitor at or slightly below eye level. To the extent possible, reduce the amount of glare on the screen, particularly from overhead lighting or windows. If glare reduction cannot be achieved by adjusting lights, drapes, or blinds, an anti-glare screen on the monitor may be helpful. Adjust the brightness of the monitor to a comfortable level for the user to reduce eye strain and fatigue. BCI users should be encouraged to take frequent visual "rest breaks" to prevent discomfort and visual fatigue [81].

Improve luminance and contrast

Modifications to the luminance and contrast ratio of the interface will be especially beneficial for users who present with reduced visual acuity, colour vision deficiency, or impaired visual field awareness. Luminance can be defined as the amount of light emanating from an object, producing the sensation of brightness [45]. Simply stated, colours have varying degrees of luminance. For example, white objects have the highest luminance rating of 1.00, black objects have the lowest rating of 0.00, and other colours have ratings in between [82]. Contrast ratio, or the difference in luminance between two objects (or between foreground and background), affects how easily a user may perceive text and other visual targets. A minimum contrast ratio of 7:1 between foreground and background [83] is recommended for optimal support for users with low visual acuity, colour deficiency, or reduced visual field [84]. For example, white text on a black background (or black text on a white background) has a contrast ratio of 21:1, indicating a high degree of contrast. Alternatively, examples of poor contrast ratios would be red (RGB 255, 0, 0) against black with a contrast ratio of 5.25:1, or blue (RGB 0, 0, 255) on black with a contrast ratio of 2.44:1. Such combinations should be avoided. Li et al. [85] provide some preliminary evidence of the potential influence of improved contrast on spelling performance while utilizing a P300 BCI for both participants without disabilities and participants with motor impairments.

Reconsider colour cues or colour combinations

Improving luminance and contrast may be beneficial if specific colours or colour combinations create challenges for visual BCI users who present with impaired colour discrimination. BCI developers should avoid certain colour combinations such as red/green, blue/purple, or green/brown, as they can be difficult to distinguish from one another [79,86]. Avoiding the use of colour alone as a distinguishing cue on an interface will help reduce confusion and potential error rates. Integrating the use of text, shape, or other features to support target discrimination will provide the user with additional cognitive cues [87].

Modify stimulus size

Modifying the size of text or other stimuli will benefit users with low visual acuity or nystagmus. Size modification can occur in one of two ways. The first is by modifying the visual angle of the stimuli, or how large they appear to the user, which is accomplished by moving the monitor closer to the user (viewing distance modification). The second is by increasing the size of the stimuli on the monitor (letter-size magnification) [88]. Although many factors can contribute to the overall preferred method for each individual user (e.g., positioning limitations imposed by the user's physical status or environment, or the user's ability to tolerate shorter viewing distances), one study found that people with low visual acuity are more likely to rely on letter-size magnification [88]. Many online resources are available to guide viewing distance or target size modifications based on acuity level. In a small, recent study [89], the effect of letter size in a P300 BCI was explored with participants without disabilities. Results suggest that stimulus size is a factor in improving spelling performance, though more research is necessary for those experiencing motor disabilities.

Although increasing the visual angle of stimuli may enhance the interface for users with reduced visual acuity, it may create difficulties for users with visual field loss. Depending upon the type, location and size of the field loss, enlarged stimuli may appear distorted or incomplete.

Modify stimulus placement

Users with visual field loss or reduced ocular motility will benefit from careful consideration of stimulus placement. Stimuli should be positioned within the user's available visual field or range of motion. Consider placing frequently used stimuli within the area of the user's gaze at rest, which often may be in the centre of the display [84].

Modify the movement of dynamic stimuli

Reducing the speed of dynamic stimuli can support those with impaired eye movements or visual field loss by allowing additional time for the user to refixate on a stimulus should it be "lost" during the visual tracking process or as it moves through an area of field loss. In addition, having dynamic stimuli move in a finite area and in a predictable pattern will allow the user to compensate for their visual field loss by learning to anticipate a target's destination. Some users may perform better with systems in which stimuli maintain fixed locations [90].

Reduce visual perceptual demand

The quality of a user's visual perceptual skills will likely be compromised if they have any degree of visual impairment. Visual BCI users may benefit from the following general suggestions to reduce visual perceptual demands:

Present simple, familiar visual stimuli
Target stimuli for visual BCI systems should be both visually simple and familiar to the user. For letter stimuli, sans-serif fonts are preferable to more visually complex fonts. Text presented in all capital letters is less familiar to most people and more difficult to read, and is best avoided [84].

Avoid visual distractions and overcrowding
Reducing extraneous visual distractions (for example, removing decorative elements or reducing the number of stimuli displayed at the same time), as well as allowing ample spacing between letters and words, can support more accurate scanning and visual processing for stimulus recognition and reading.

Allow additional time for information processing
Some users may benefit from additional time to process visual information. This may involve slowing animation speeds or presentation rates, or adding pauses after letter selection or at other times during system use. If system messages or task instructions are presented visually, additional time may be required to read text or visually process information in a symbol, diagram, or video.

Conclusion

As BCI research activities continue to grow and systems begin to enter clinical practice, it is critical to understand technology performance, user performance, and the interactions between the two [91]. For assistive technologies such as BCI that rely on a visual interface for information presentation, an awareness of the visual skills that are required for adequate use is essential [92]. We encourage thoughtful consideration of how a user's specific visual impairments may affect the use of a visual BCI, and use of a person-centred feature-matching approach to interface customization, as demonstrated by Brumberg et al. [18]. The information and recommendations presented here are only the beginning. In order for BCI technology to achieve its promise as an AT for people with SSPI, systems must be customizable, and researchers and clinicians must understand how to adapt those systems to individual users' needs and abilities.

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