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A comparison of stimulus sequences for code-modulated visual evoked potential (c-VEP) based BCI

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Introduction: The code-modulated visual evoked potential (c-VEP) is an evoked response observed in the EEG in response to rapid visual stimulation with a pseudo-random sequence of flashes [1]. Contrary to ERP protocols, c-VEP stimulation is faster. Opposed to SSVEP protocols, c-VEP stimulation is non-periodic. Consequently, c-VEPs allow higher bandwidth. To make full use of the potential of c-VEPs, it is important to consider the vast choice of stimulus sequences. Typically, sequences from telecommunication are used like m-sequences or Gold codes [1]. However, it is often ignored that these sequences are optimized in the digital stimulus domain, while good BCI performance largely depends on good correlation properties in the EEG response domain. Carry-over between these domains is not a given. Unfortunately, however, to date there is no good understanding of which stimulus sequence leads to optimal BCI performance.

Material, Methods and Results: We recorded 64-channel EEG data from 16 participants who were shown a 4x8 matrix speller with 10 different stimulus sequences at 60 Hz. Code-families were (1) a shifted m-sequence, (2) a shifted Gold code, (3) a set of Gold codes, (4) a shifted de Bruijn sequence, and (5) a shifted Golay sequence. Codes were presented as either original or as modulated via XOR with a double-frequency bit-clock to limit low-frequency content [2]. For each condition, 32 4.2-second trials were recorded to offline estimate decoding curves using an 8-fold cross-validation with a template-matching classifier using reconvolution [2, 3] and canonical correlation analysis. The highest average information transfer rate (ITR) was obtained with an m-sequence (118 bits/min), followed by a Golay sequence (114 bits/min), Gold code (107 bits/min), de Bruijn sequence (97 bits/min) and Gold code set (82 bits/min). Additionally, overall, modulation of codes did not affect ITR compared to original codes ($p > .100$).

Discussion: The results suggest that the performance of a c-VEP BCI significantly depends on the sequences that are used for the stimulus protocol. Moreso, the code family that is optimal varies largely over participants, which suggests the necessity to optimise the stimulus protocol for individual users instead of the entire population of users. Such subject-specific optimization may lead to substantially higher ITRs. Further research is foreseen to gain insight into why certain stimulus sequences lead to improved performance. In turn, these insights may lead to inspiration for even better performing handcrafted stimulus sequences and ultimately faster c-VEP BCI.

Significance: Optimizing the c-VEP stimulus protocol for individuals leads to higher communication rates and may initiate more practical BCI applications for communication and control. Moreso, this and other improvements make c-VEP protocols a likely candidate to replace existing protocols such as ERP and SSVEP due to its obvious advantages with respect to reliability, speed, and scaling to large number of classes.

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